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# Relations Among Geology, Physiography, Land Use, and Stream Habitat Conditions in the Buffalo and Current River Systems, Missouri and Arkansas

**Biological Science Report**
**USGS/BRD/BSR–2001-0005**

**Prepared in cooperation with the National Park Service, Midwestern Region; Buffalo National River and Ozark National Scenic Riverways**

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

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July 2001

By Maria S. Panfil and Robert B. Jacobson

Prepared in cooperation with the National Park Service, Midwestern Region; Buffalo National River and Ozark National Scenic Riverways

U.S. Geological Survey
Biological Resources Division
Columbia Environmental Research Center
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## Conversion Factors and Vertical Datum

| Multiply | By | To obtain |
|---|---|---|
| **Length** | | |
| millimeter (mm) | 0.03937 | inch |
| meter (m) | 3.281 | foot |
| kilometer (km) | 0.6214 | mile |
| **Area** | | |
| square meter ($m^2$) | 10.76 | square foot |
| square kilometer ($km^2$) | 0.3861 | square mile |
| **Flow rate** | | |
| cubic meter per second ($m^3/s$) | 35.31 | cubic foot per second |
| **Hydraulic gradient** | | |
| meter per kilometer (m/km) | 5.27983 | foot per mile |

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

°F = (1.8 x °C) + 32

**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.

# Relations Among Geology, Physiography, Land Use, and Stream Habitat Conditions in the Buffalo and Current River Systems, Missouri and Arkansas

**Abstract:** This study investigated links between drainage-basin characteristics and stream habitat conditions in the Buffalo National River, Arkansas and the Ozark National Scenic Riverways, Missouri. It was designed as an associative study - the two parks were divided into their principle tributary drainage basins and then basin-scale and stream-habitat data sets were gathered and compared between them. Analyses explored the relative influence of different drainage-basin characteristics on stream habitat conditions. They also investigated whether a relation between land use and stream characteristics could be detected after accounting for geologic and physiographic differences among drainage basins.

Data were collected for three spatial scales: tributary drainage basins, tributary stream reaches, and main-stem river segments of the Current and Buffalo Rivers. Tributary drainage-basin characteristics were inventoried using a Geographic Information System (GIS) and included aspects of drainage-basin physiography, geology, and land use. Reach-scale habitat surveys measured channel longitudinal and cross-sectional geometry, substrate particle size and embeddedness, and indicators of channel stability. Segment-scale aerial-photo based inventories measured gravel-bar area, an indicator of coarse sediment load, along main-stem rivers. Relations within and among data sets from each spatial scale were investigated using correlation analysis and multiple linear regression.

Study basins encompassed physiographically distinct regions of the Ozarks. The Buffalo River system drains parts of the sandstone-dominated Boston Mountains and of the carbonate-dominated Springfield and Salem Plateaus. The Current River system is within the Salem Plateau. Analyses of drainage-basin variables highlighted the importance of these physiographic differences and demonstrated links among geology, physiography, and land-use patterns. Buffalo River tributaries have greater relief, steeper slopes, and more streamside bluffs than the Current River tributaries. Land use patterns in both river systems correlate with physiography - cleared land area is negatively associated with drainage-basin average slope. Both river systems are dominantly forested (0-35 percent cleared land), however, the potential for landscape disturbance may be greater in the Buffalo River system where a larger proportion of cleared land occurs on steep slopes (>15 degrees).

When all drainage basins are grouped together, reach-scale channel characteristics show the strongest relations with drainage-basin physiography. Bankfull channel geometry and residual pool dimensions are positively correlated with drainage area and topographic relief variables. After accounting for differences in drainage area, channel dimensions in Buffalo River tributaries tend to be larger than in Current River tributaries. This trend is consistent with the flashy runoff and large storm flows that can be generated in rugged, sandstone-dominate terrain. Substrate particle size is also most strongly associated with physiography; particle size is positively correlated with topographic relief variables.

When tributaries are subset by river system, relations with geology and land use variables become apparent. Buffalo River tributaries with larger proportions of carbonate bedrock and cleared land area have shallower channels, better-sorted, gravel-rich substrate, and more eroding banks than those with little cleared land and abundant sandstone bedrock. Gravel-bar area on the Buffalo River main stem was also larger within 1-km of carbonate-rich tributary junctions. Because geology and cleared land are themselves correlated, relations with anthropogenic and natural factors could often not be separated.

Channel characteristics in the Current River system show stronger associations with physiography than with land use. Channels are shallower and have finer substrates in the less rugged, karst-rich, western basins than in the steep, middle and eastern basins. Gravel-bar distributions are more consistent with hypothesized lagged, historical effects than with recent impacts from land use. Temporal comparisons of 1992 and 1996 gravel-bar distributions show downstream translation of gravel after a 50-year flood. Gravel-bar area is also more strongly related to tributary characteristics when measured at longer distances downstream of tributary junctions.

This analysis indicates that physiography and size are the primary controls on stream characteristics in the Ozarks. For the rural landscape of the study basins, land use appears to exert a subtle influence notable only when streams are subset into physiographic groups. Channel characteristics and gravel-bar area in the Buffalo River system are more consistent with a model of contemporary land-use effects than those in the Current River system. However, relations among land-use patterns, geology, and physiography make it difficult to separate anthropogenic from natural impacts on streams.

**Keywords:** land use change, aquatic habitat, geomorphology, hydrology, Ozarks, Missouri, Arkansas

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# Introduction

The Buffalo National River and Ozark National Scenic Riverways were created to preserve and interpret the free flowing Buffalo, Jacks Fork, and Current Rivers. Clear waters and diverse ecosystems are the primary resources of these national parks – they provide canoeing and fishing opportunities that attract millions of visitors annually and are an important preserve for biodiversity in the mid-Continent (fig. 1). Ozark streams host approximately 175 native and introduced fish species of which at least 19 are endemic (Petersen, 1998).

Preservation of water quality and aquatic ecosystems are among the highest priorities and greatest challenges for the parks. Designed as river corridors, much of the drainage basins that determine water quality and aquatic habitat characteristics are outside of park boundaries and unprotected from land-use changes that may affect the rivers. In the Buffalo River drainage basin, for example, only 11 percent of the drainage area is within the park, while 23 percent is held by other state and federal agencies, and the remaining 66 percent is privately owned. Areas outside the park boundaries have undergone significant land-use changes in recent decades and this has raised concern that erosion and non-point source pollution threaten the park's resources. In the Buffalo, about 11 percent of the drainage basin (375 square kilometers/92,780 acres) was converted from forest to pasture between 1965 and 1992 and there has been a trend toward the clearing of steeper, more erodible lands (Scott and Hofer, 1995). Resource managers at both national parks are in the process of developing Water Resources Management Plans to guide river-conservation strategies. One of the goals of the plans is to help the parks facilitate basin-wide discussions with their drainage-basin communities. To do this, plans need to present and evaluate resource-management concerns such as the impact of land-use changes on river conditions and habitat quality. This study was initiated in 1999 through the USGS Natural Resources Preservation Program to address some of the science information needs of these management concerns.

## Purpose and General Scope

The main objectives of the study were to inventory drainage basin and stream-habitat conditions in the two parks and evaluate links between land use and stream-habitat quality in the context of the many complex natural factors that influence streams. It was designed as a comparison study – the two rivers were divided into their principle tributary drainage basins and then basin-scale and stream-habitat data sets were gathered and compared between them (fig. 2). Specific objectives of this study included:

- Compilation of a geospatial database and inventory of basin-scale characteristics likely to influence stream conditions. A geographic information system (GIS) was used to summarize and compare aspects of geology, physiography, and land use for 43 major tributary drainage basins of the parks.
- Development of a reach-scale[1], field inventory of physical habitat conditions in 36 of the parks' major tributaries. The inventory included measures of channel geometry, substrate, and channel stability.
- Development of a segment-scale[2], aerial photo based inventory of gravel-bar area along the park's main-stem rivers. Gravel-bar area is an indirect measure of coarse sediment load in the river systems.

This report presents data collected for each of these project components and analyzes relations between them. Basin-scale analyses include a description of the geology and physiography of the two river systems and an analysis of how these factors influence land-use patterns in the park drainage basins. Stream analyses include descriptions of reach and segment-scale stream characteristics and analyses of relations between stream conditions and drainage-basin geology, physiography, and land use.

## Stream Geomorphology and Aquatic Habitats

Aquatic communities are affected by the chemical, physical, and biological conditions of their habitat. This project focuses on physical habitat – the combination of depth, velocity, substrate, and cover – because it is thought to be a major determinant of stream community potential (Schlosser, 1987; Plafkin and others, 1989). While other factors such as water chemistry and interspecies competition can also influence stream biota,

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[1] Reaches are defined as contiguous lengths of river with one or more repeating sequences of similar channel units or macrohabitats (Frissel and others, 1986). In this project, reaches included a minimum of three riffle-pool sequences or a distance of at least 20 bankfull channel widths.

[2] Segments are defined as lengths of river characterized by limited variation in hydrologic and physiographic characteristics, for example lengths of stream between tributary junctions (Frissel and others, 1986). In this project, segments included 0.2-4.8 km lengths of main-stem rivers downstream of each tributary junction.

community-level structural patterns often correlate strongly with physical habitat variables (for example, Schlosser, 1982; Statzner and Higler, 1986). Generally, an increase in species diversity is associated with an increase in physical habitat diversity (Gorman and Karr, 1978; Schlosser, 1987; Jeffries and Mills, 1990).

Whereas the structure and distribution of stream habitats shape the community, geomorphic theory suggests that the habitat conditions themselves are controlled by drainage-basin characteristics (for example, Leopold and others, 1964). Streams act as conveyor belts moving sediment and water through the landscape. Channel morphology, substrate, and discharge, and therefore habitat conditions, reflect the balance of sediment supply and streamflow contributed by the drainage basin. Many natural landscape characteristics affect this balance. Aspects of geology and physiography influence how rainfall is routed to streams and determine the types and quantities of sediment introduced into the system (table 1). Humans may modify the sediment/hydrology balance by changing vegetation types, ground permeability, or altering the drainage network (table 1). In a rippling effect, landscape changes can then translate from uplands to streams and their biota.

It can be a challenge to document links between many anthropogenic disturbances and stream processes (for example, Jacobson and others, 2001). Monitoring of hydrologic changes require stream gages, preferably with extensive records pre-dating and post-dating the landscape disturbance. Bedload sediment studies introduce the logistical challenges of measuring tons of gravel or sand in flux over the streambed. It is also difficult in drainage-basin studies to obtain replicates or control for differences in geologic or physiographic characteristics. Moreover, landscapes are subject to disturbance from natural, stochastic meteorological events that can cause highly variable stream conditions that need to be separated from human-induced effects (for example, Fitzpatrick and Knox, 2000).

In the absence of instrumental records or controlled experiments, many studies have undertaken an associative approach (for example, Allan and others, 1997; Fitzpatrick and others, 1996; Lammert and Allan, 1999; Roth and others, 1996; Richards and others, 1993; Richards and Host, 1994; Richards and others, 1996). At the drainage-basin scale, these studies identified potential controls on sediment yield and hydrology and then compared these factors with reach-scale inventories of stream habitat and/or biological communities. They used statistical techniques to identify relations between the two scales. Many of these studies focused on biological communities and evaluated physical habitat conditions qualitatively. This project follows these studies' associative approach but differs in three main ways: it emphasizes quantitative measures of physical habitat conditions, focuses on the link between drainage-basin characteristics and physical habitat conditions rather than on the sequential link to biota, and investigates disturbance in a landscape characterized by relatively subtle variation in land use.

The physical habitat measures in this study relate to three categories of channel change that anthropogenic disturbances are thought to trigger. These include: changes in channel geometry, changes in substrate characteristics, and a loss of channel stability (table 2; for example, Schumm, 1977; Lisle, 1982). Multiple, sometimes contradictory outcomes are possible depending on whether landscape disturbance increases streamflow and transport capacity relative to sediment supply or whether the balance is tipped in the opposite direction (table 1).

## Regional Setting and Climate

The Ozark Highlands Physiographic Province is a rugged, montane region largely made up of Paleozoic sedimentary rocks. The climate is continental and is predominantly affected by east moving storm systems that often include thunderstorms with short bursts of intense rainfall. Mean annual precipitation is 1000-1200 millimeters for Rolla, Missouri (80 years of record) with mean annual temperatures between 15-18 degrees Celsius (Jacobson and Pugh, 1992). The Ozarks are commonly divided into four physiographic regions: the Boston Mountains – an area with high relief and butte-like sandstone uplands, the St. Francois Mountains – a bulls eye shaped region of Proterozoic igneous rocks, and the Springfield and Salem Plateaus – region's dominated by expansive rolling uplands and carbonate rocks (fig. 1). Elevations in the Ozarks range between 150 meters above sea level in the north along the Mississippi River to about 720 meters above sea level in the Boston Mountains.

A karst drainage system underlies most of the Ozarks and combines with the rugged topography to create a wide range of aquatic environments. In many ways, the Buffalo National River (BNR) and the Ozark National Scenic Riverways (ONSR) represent extremes in this spectrum. The ONSR includes the Current River and its primary tributary the Jacks Fork (fig. 1). Flow from springs makes up a substantial portion of the baseflow in these rivers. In fact, springs maintain low enough temperatures in the upper Current to support a trout population. In contrast, much less of the baseflow in the Buffalo River comes from springs and water temperatures are warmer. The Buffalo is noted for its spectacular bluffs and its "flashy" floods generated by

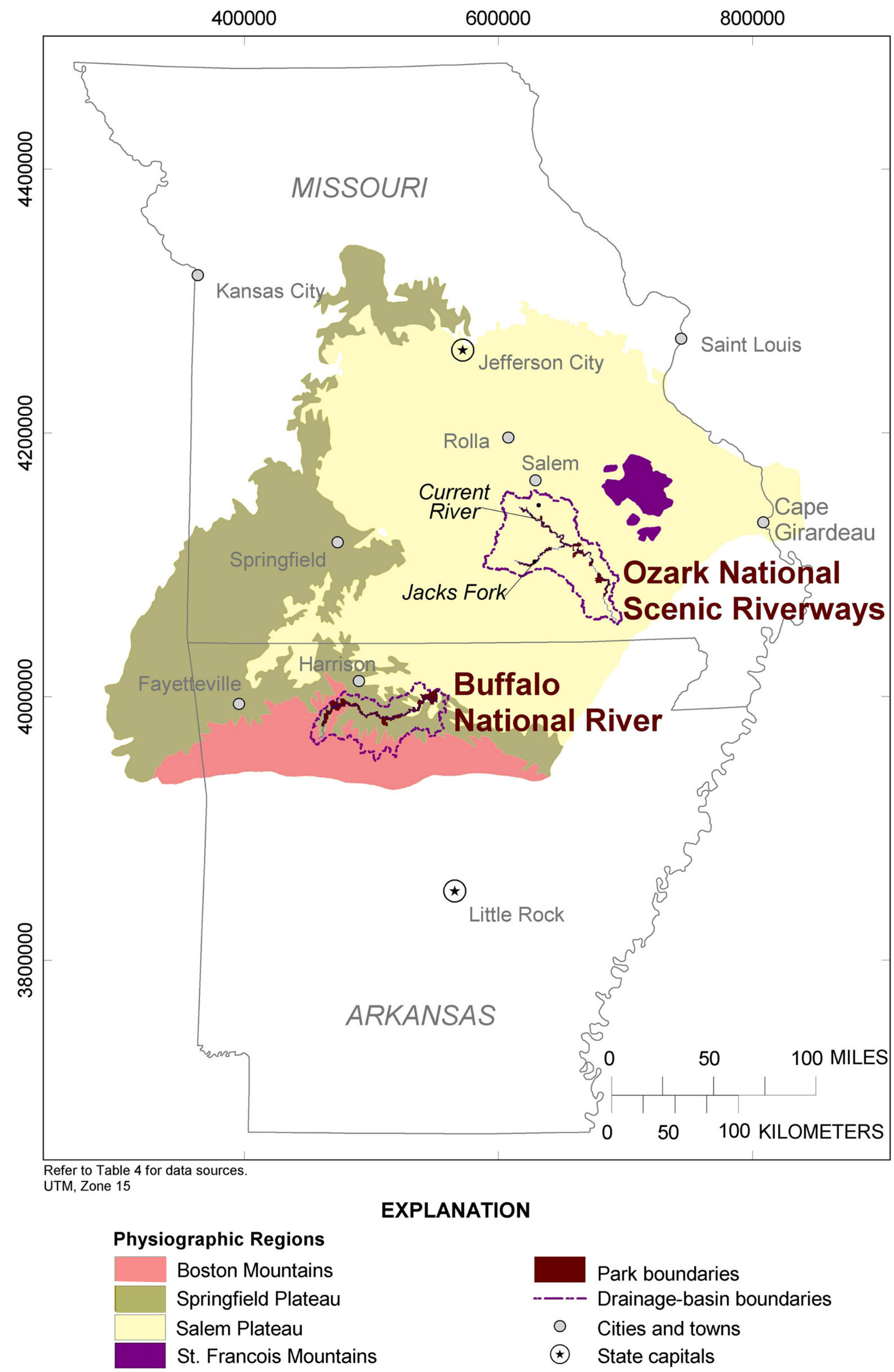



**Figure 1.** Location map for the Ozark National Scenic Riverways and the Buffalo National River. The two parks are within different physiographic regions of the Ozark Highlands.

runoff from the basin's steep topography.

Despite their differences, both drainage basins have experienced similar land-use histories. Prior to European settlement around 1800, humans lived as hunters and gatherers in caves and in small villages on river terraces. European settlers cleared valley bottoms for pasture and row crops and began to cut timber from valley slopes. Construction of railroads in the 1870's led to increased logging and clearing and a surge in population between 1880 and 1920. Commercial timber companies harvested shortleaf pine for sawlogs and oak for railroad ties. In the post-timber boom period (1920-1960), Ozarks residents returned to agriculture, instituting annual burning of uplands and increasing grazing on open ranges. Although the open range has been closed and cultivated fields have decreased since 1960, cattle populations and timber operations have increased (Scott and Hofer, 1995; Jacobson and Primm, 1997). In the last half of the 20th Century, tourism also became an important economic activity. During 1998 over 2 million people visit ONSR and BNR to canoe, fish, camp on gravel bars, and enjoy the beauty of the steep-sided hollows, bluffs, and clear-water streams.

# Methods

This study collected drainage-basin data, reach-scale stream-habitat data, and segment-scale data for main-stem rivers (fig. 2). Basin-scale and reach-scale data sets focused on tributaries as a way to subset the river systems into independent drainage basins and their associated stream reaches. Study drainage basins included the major tributaries of the Jacks Fork, Current, and Buffalo Rivers and were chosen to maximize drainage area, match locations of on-going water-quality monitoring sites (for example, Mott, 1997), and facilitate site access. Basin-scale analyses were carried out for 19 tributary drainage basins in the Buffalo River System and 24 tributary drainage basins in the Current (figs. 3 and 4). A reach-scale, field habitat inventory was carried out near the mouth of 19 tributaries of the Buffalo River system and 17 tributaries of the Current River system. Seven tributaries in the Current River system were dropped from the reach-scale project component because of difficulties with site access or intermittent stream flow (table 3, figs. 3 and 4).

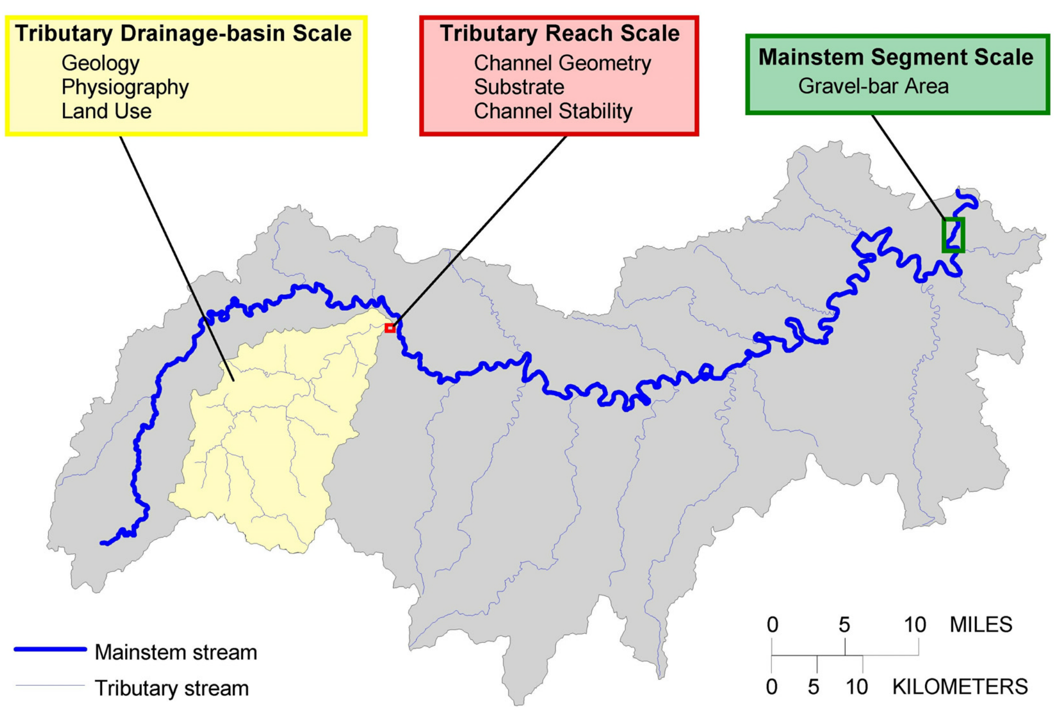



**Figure 2.** Map illustrating the three spatial scales of data collection. Basin-scale data was collected for major tributaries. Reach-scale data was collected on these tributaries near their junctions with main-stem rivers. Segment-scale data was collected along the main-stem rivers themselves.

**Table 1**. Drainage-basin characteristics measured in this study and their potential effects on geomorphic processes in the Ozarks

| Variable | Hydrology | | Sediment Supply | |
|---|---|---|---|---|
| | Base flow[i] | Storm flow | Upland Supply | Lowland Supply |
| | | **Geology** | | |
| Carbonate bedrock area | Landscape position of carbonates and contacts with other lithologies influence the distribution of karst features. | | The carbonate formations contain chert, the highly resistant microcrystalline quartz that forms much of the gravel in Ozarks streams. | |
| | | **Physiography**[ii] | | |
| Drainage area | Determines the amount of rainfall intercepted by the stream basin and therefore is one of the greatest controls on base flow. | As with base flow, basin area controls runoff and storm flow. Basin area also affects hydrograph shape; larger basins tend to have less flashy storm flow because they integrate runoff from a larger area. | Due to abrasion and selective transport, there tends to be a "downstream fining" trend where grain size is inversely correlated with drainage area (for example, Knighton, 1984). | Larger basins tend to have wider stream valleys and more sediment available for remobilization from flood-plain storage. |
| Drainage-basin shape factor | | Influences storm flow routing and the flashiness of storm hydrographs. Storm flow peaks decrease as network length and flow travel time increase. | Influences sediment routing through the drainage network. | |
| Average drainage-basin slope | | Steep slopes increase runoff and decrease flow travel time and therefore tend to increase storm flow peaks. | Steep slopes increase the shear stress generated by runoff and the potential for sediment detachment and entrainment. | |
| Elevation range | | | Greater elevation ranges create greater potential energy over the length of the stream network. | |
| Bluff area in stream buffer | | | | Bluffs provide a proximal source of coarse sediment in Ozarks streams and influence channel morphology and sediment storage (for example, McKenney, 1997). |

[i] Streamflow is assumed here to be equal to base flow (flow from ground water) plus storm flow (flow from overland runoff).
[ii] Overview discussions of drainage-basin controls on stream hydrology and sediment load can be found in USDA (1972) and Meade and others (1990).

**Table 1**. Drainage-basin characteristics measured in this study and their potential effects on geomorphic processes in the Ozarks--Continued

| Variable | Hydrology | | Sediment Supply | |
|---|---|---|---|---|
| | **Base flow** | **Storm flow** | **Upland Supply** | **Lowland Supply** |
| | | **Land Use** | | |
| Cleared land area | Timber cutting can decrease evapotranspiration and increase base flow until groundcover is reestablished (for example, Keppler, 1998). | Timber cutting can increase storm flow (for example, Settengren and others, 1980; Jones and Grant, 1996). Reduced groundcover and soil compaction in pastures can decrease infiltration and increase runoff (for example, USDA, 1972). | Reduced groundcover can increase erosion from rainsplash and overland flow (for example, Dunne and others, 1978). It may also increase the likelihood of gully initiation (for example, Reid, 1989). | |
| Steep cleared land area | | | Reduced groundcover and increased ground disturbance can increase sediment availability. Entrainment and transport is facilitated on steep slopes where runoff can generate high shear stresses. | |
| Cleared land area within stream buffers | | | In Ozark streams, intensive grazing in riparian areas may be associated with headwater extension of the drainage network (Jacobson and Primm, 1997). | Grazing or other buffer disturbances can destabilize stream banks (for example, Waters, 1995). |
| Road density in drainage basin | | Roads can act as artificial channels, accelerate flow convergence, and increase runoff (for example, Jones and Grant, 1996; Wemple and others, 1996). | Roads can act as artificial channels that accelerate flow convergence and increase sediment delivery to streams (for example, Dunne, 1979; Megahan and Kidd, 1972). | |
| Road density in stream buffer | | | | Road crossings can destabilize stream banks. Runoff from streamside roads can increase sediment delivery to streams (for example, Waters, 1995). |

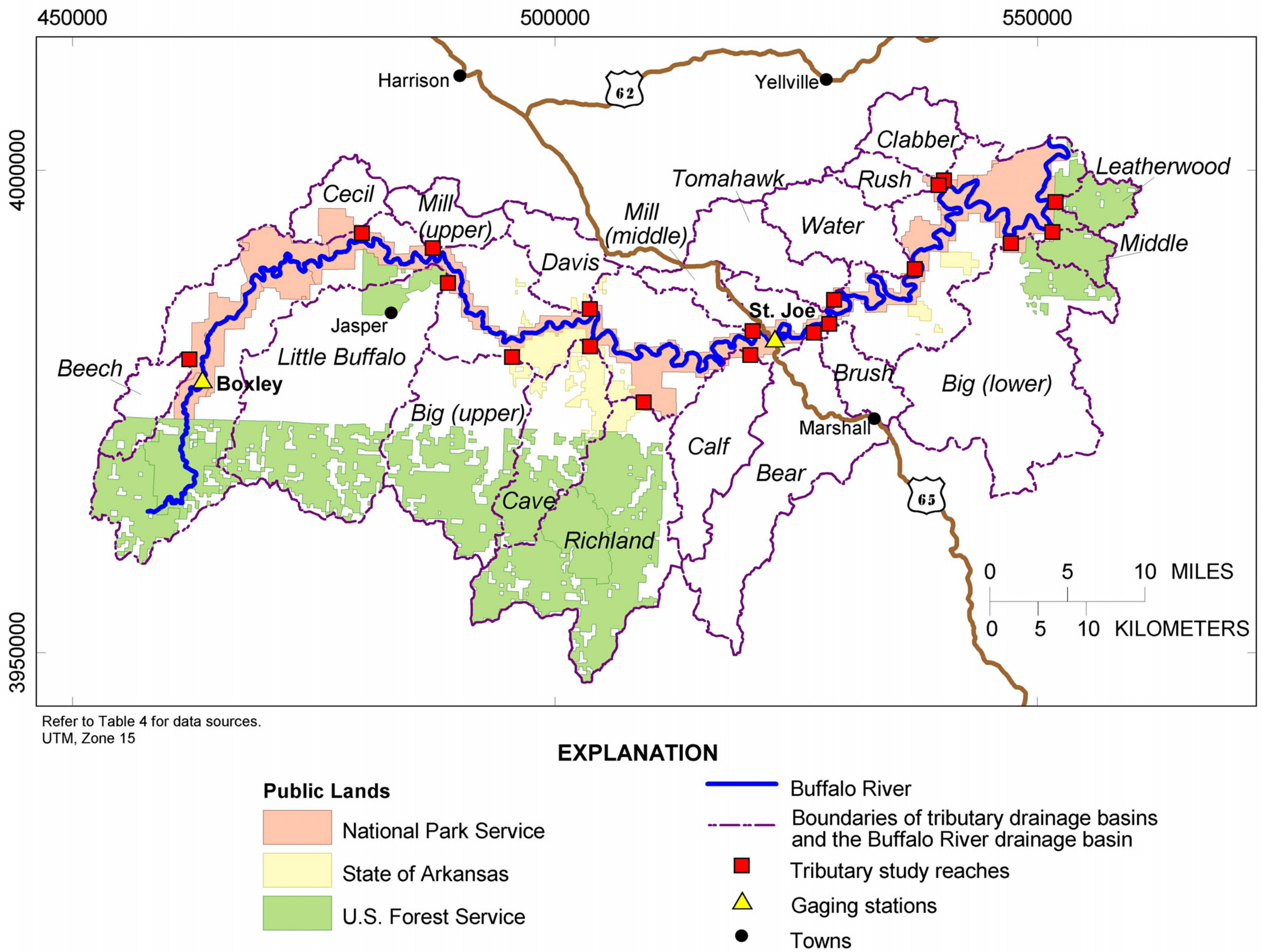



**Figure 3.** Map of the Buffalo River drainage basin showing study sites and public lands.

**Table 2**. Potential effects of human induced change on Ozarks stream geomorphology and biota and related habitat measurements

| Disturbance | Potential Impacts on Stream Geomorphology | Potential Implications for Stream Biota | Related Habitat Variables[i] | |
|---|---|---|---|---|
| More fine sediment introduced into the stream system. | May create embedded substrates. | Embeddedness reduces the pore space between gravel and cobble particles that is available as living spaces.<br><br>Embeddedness may also inhibit flow of oxygenated waters through stream-bed gravel. | Embeddedness in glides<br>Embeddedness in thalweg<br>Mud and sand in thalweg<br>Glide D16<br>Point Bar D16 | **Substrate** |
| More gravel introduced into the stream system. | Overall reduction in the average particle size of substrate as cobbles are buried or infiltrated with fine and medium gravel.<br><br>Loss of particle size diversity as substrate becomes dominated by gravel. | Loss of coarse substrates and the larger pore spaces they create. | Gravel in thalweg<br>Cobbles and boulders in thalweg<br>Glide D50<br>Glide D84<br>Point Bar D50<br>Point Bar D84<br>Glide sorting<br>Point bar sorting | **Substrate** |
| | Greater volumes of gravel in streams may fill in channels, making pools shallower and reducing longitudinal channel roughness.<br><br>More base flow may flow through the subsurface in streams with thick gravel deposits creating shallower streams. | Change in the distribution and abundance of habitat types and loss of habitat diversity. In particular, greater volumes of gravel may increase the availability of glide habitats and decrease the availability of pools.<br><br>Shallower pools reduce the living space available for pool dependent species.<br><br>Shallower streams may have greater daily and season fluctuations in water temperature. | Residual pools<br>Average residual pool length<br>Average residual pool depth<br>Average bankfull depth<br>Average bankfull width<br>Pool habitats<br>Glide habitats<br>Mainstem gravel bar area | **Channel Geometry** |
| Loss of coarse woody debris from the stream system. | Fewer debris jams and snags to create flow diversity and initiate the scour that forms obstruction pools. | Loss of living spaces in debris jams.<br><br>Loss of obstruction pools and lower habitat diversity. | Obstruction pools | **Channel Geometry** |

[i] Refer to table 5 for variable definitions.

**Table 2**. Potential effects of human induced geomorphic change on Ozarks streams and their physical habitat--Continued

| Disturbance | Potential Impacts on Stream Geomorphology | Potential Implications for Stream Biota | Related Habitat Variables |
|---|---|---|---|
| **Channel Stability** | | | |
| Increased storm flows. | May increase the frequency of bed-mobilization. | May increase the disturbance frequency of benthic habitats. | Eroding banks<br>Bank vegetation index |
| | May create peak discharges that are more erosive and more likely to destabilize stream banks. Stream banks may become a source of both fine and coarse sediment as flood plain deposits erode. | Fine sediment may create more embedded habitats (see above).<br>Coarse sediment may trigger changes in habitat geometry (see above). | |
| | Stream bank erosion may lead to stream widening, reduction in channel sinuosity and loss of canopy cover. | May create shallower, warmer habitats and lower habitat diversity. | Reach sinuosity<br>Canopy cover in glides |

## Basin-Scale Data Collection

We used a geographic information system (GIS) to characterize drainage-basin characteristics that may influence physical habitat. Using Arc/Info 7.2 and ArcView 3.2[3] software (Environmental Research Systems Institute, 1998a, 1998b), we measured aspects of drainage-basin physiography, land use, geology, roads, stewardship, drainage networks, and soils (table 4). Data layers were collected from a variety of sources including: the U.S. Geological Survey (USGS), the U.S. Environmental Protection Agency (EPA), the U.S. Census Bureau (USCB), the Missouri Resource Assessment Partnership (MoRAP), the Center for Advanced Spatial Technologies (CAST), and the Natural Resources Conservation Service (NRCS) (table 4). We chose data layers to maximize resolution but maintain consistency between the Buffalo and Current River systems. In some cases this meant foregoing the highest resolution data set for one river system if it was not available for both. For example, a continuous 1:24,000-scale stream network is available for the Current River drainage basin but it is not yet available for Arkansas; therefore, we worked with the 1:100,000-scale EPA river-reach files.

Initially, sixty-four basin-scale variables were considered that had been incorporated into other drainage-basin assessments (Warner and others, 1996; Fitzpatrick and others, 1998). This large number of variables was reduced by eliminating ones with similarities or whose utility was limited by data resolution. For example, we eliminated soils variables from our analysis because the resolution of the GIS data set appeared too coarse to identify differences between study drainage basins. Soil characteristics were measured from 1:250,000-scale STATSGO soils database (U.S. Department of Agriculture, 1994a, 1994b) and included soil permeability and erodibility variables as suggested by Fitzpatrick and others (1996). Calculation of these variables involved multiple averaging, first to integrate maximum and minimum measurements for each soil layer and then to integrate measurements for each soil type within a drainage basin. After this sequence of averaging there was little difference in variables between study drainage basins in this data set. Resolution also hindered measurements of stream networks. There were inconsistent differences in detail between areas of the 1:100,000-scale EPA river-reach files, therefore stream network-based variables were not selected for analysis (table 4). The following paragraphs provide more details about the variables selected for comparison with the reach-scale habitat inventory data.

[3] Use of tradenames is for informational purposes only and does not constitute an endorsement by the U.S. Geological Survey.

**Table 3**. Selected characteristics of Buffalo and Current River tributary sites; streams were organized into physiographic groups according to location, elevation range, and drainage basin average slope

[$km^2$, square kilometers; m, meters; NA, not applicable]

| Tributary | Carbonate bedrock area (percent) | Drainage area ($km^2$) | Private land area (percent) | Cleared land area (percent) | Reach length (m) | Reach gradient (m/m) | Bedrock in thalweg (percent) |
|---|---|---|---|---|---|---|---|
| **Buffalo, Boston Mountains** | | | | | | | |
| Bear Creek | 28 | 238 | 100 | 28 | 552 | 0.0024 | 6 |
| Beech Creek | 3 | 49 | 72 | 7 | 455 | 0.0093 | 36 |
| Big Creek (Lower) | 63 | 346 | 91 | 26 | 661 | 0.0016 | 24 |
| Big Creek (Upper) | 21 | 230 | 58 | 13 | 743 | 0.0013 | 3 |
| Calf Creek | 34 | 124 | 98 | 31 | 491 | 0.0019 | 0 |
| Cave Creek | 34 | 134 | 44 | 11 | 883 | 0.0017 | 35 |
| Cecil Creek | 19 | 57 | 80 | 13 | 421 | 0.0061 | 10 |
| Davis Creek | 64 | 72 | 98 | 18 | 252 | 0.0048 | 3 |
| Little Buffalo River | 17 | 369 | 69 | 9 | 1197 | 0.0013 | 9 |
| Mill Creek (upper) | 61 | 54 | 98 | 16 | 438 | 0.0029 | 31 |
| Richland Creek | 3 | 313 | 22 | 5 | 1135 | 0.0009 | 0 |
| **Buffalo, Springfield and Salem Plateaus** | | | | | | | |
| Brush Creek | 89 | 50 | 100 | 32 | 433 | 0.0043 | 3 |
| Clabber Creek | 26 | 67 | 99 | 23 | 486 | 0.0083 | 44 |
| Leatherwood Creek | 37 | 32 | 6 | 0 | 383 | 0.0054 | 7 |
| Middle Creek | 43 | 29 | 3 | 0 | 256 | 0.0106 | 49 |
| Mill Creek (middle) | 64 | 36 | 100 | 32 | 358 | 0.0041 | 0 |
| Rush Creek | 77 | 36 | 96 | 11 | 314 | 0.0057 | 0 |
| Tomahawk Creek | 67 | 95 | 99 | 33 | 479 | 0.0033 | 3 |
| Water Creek | 78 | 99 | 99 | 22 | 522 | 0.0045 | 19 |
| Buffalo River | 39 | 3469 | 66 | 15 | NA | NA | NA |

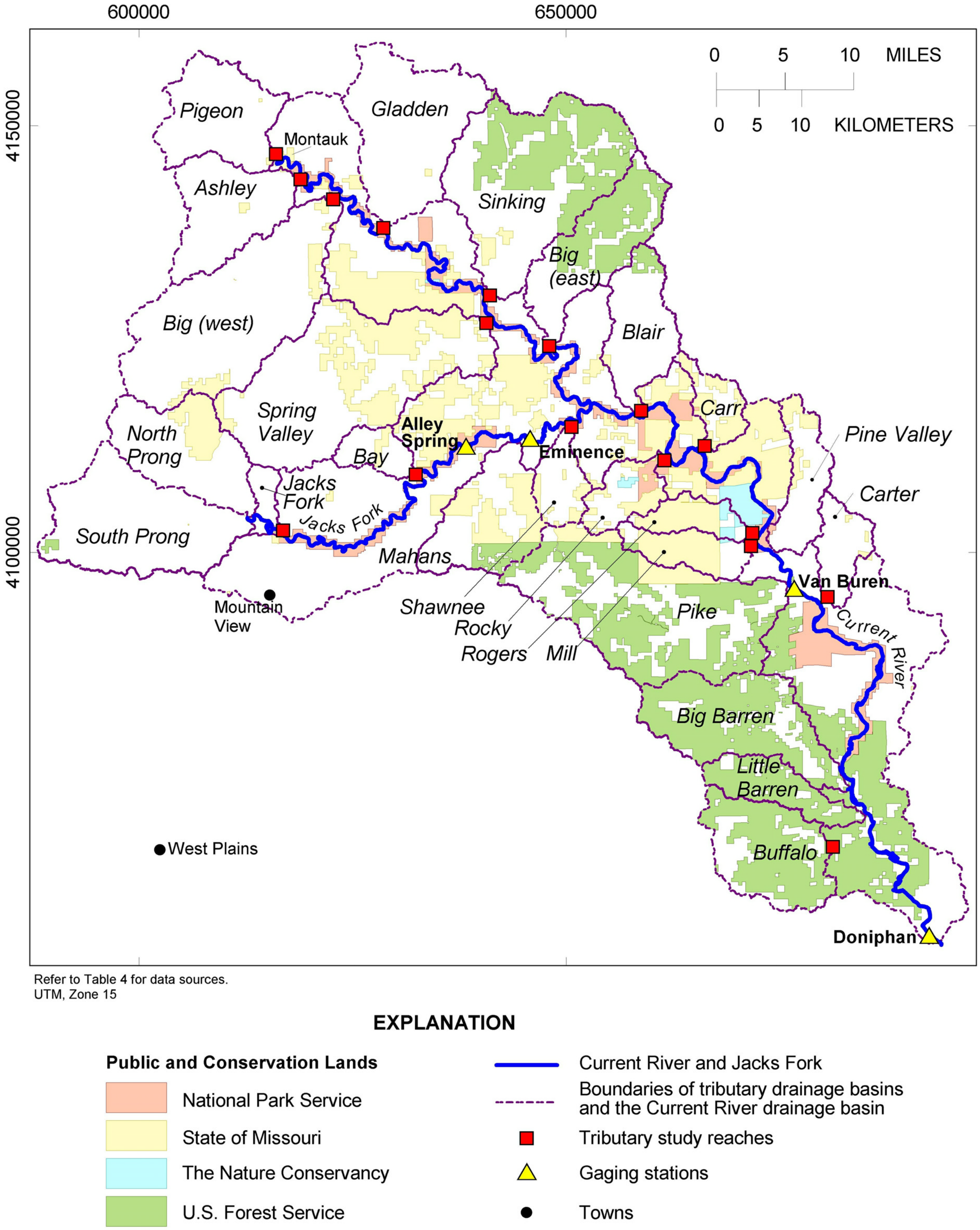
**Table 3**. Selected characteristics of Buffalo and Current River tributary sites; streams were organized into physiographic groups according to location, elevation range, and drainage basin average slope--Continued

| Tributary | Carbonate bedrock area (percent) | Drainage area ($km^2$) | Private land area (percent) | Cleared land area (percent) | Reach length (m) | Reach gradient | Bedrock in thalweg (percent) |
|---|---|---|---|---|---|---|---|
| **Current, West** | | | | | | | |
| Ashley Creek | 36 | 138 | 99 | 24 | 456 | 0.0020 | 1 |
| Bay Creek | 21 | 40 | 88 | 16 | 317 | 0.0090 | 3 |
| Big Barren Creek[1] | 10 | 191 | 22 | 4 | NA | NA | NA |
| Big Creek (west) | 58 | 333 | 93 | 25 | 503 | 0.0019 | 0 |
| Buffalo Creek | 39 | 153 | 28 | 6 | 654 | 0.0021 | 0 |
| Gladden Creek | 57 | 218 | 99 | 35 | 419 | 0.0023 | 0 |
| Jacks Fork River[2] | 61 | 406 | 92 | 23 | 948 | 0.0019 | 2 |
| Little Barren Creek[1] | 29 | 75 | 15 | 5 | NA | NA | NA |
| North Prong Jacks Fork River[1] | 77 | 152 | 80 | 27 | NA | NA | NA |
| Pigeon Creek | 17 | 140 | 99 | 33 | 576 | 0.0024 | 2 |
| Pike Creek[1] | 26 | 364 | 40 | 11 | NA | NA | NA |
| South Prong Jacks Fork River[1] | 47 | 229 | 99 | 20 | NA | NA | NA |
| Spring Valley Creek | 55 | 369 | 69 | 32 | 463 | 0.0024 | 10 |
| **Current, Middle and East** | | | | | | | |
| Big Creek (east) | 93 | 152 | 48 | 4 | 506 | 0.0026 | 0 |
| Blair Creek | 89 | 112 | 91 | 1 | 397 | 0.0021 | 0 |
| Carr Creek | 88 | 46 | 36 | 5 | 247 | 0.0045 | 0 |
| Carter Creek | 42 | 57 | 97 | 8 | 169 | 0.0033 | 0 |
| Mahans Creek[1] | 57 | 140 | 56 | 6 | NA | NA | NA |
| Mill Creek | 81 | 61 | 29 | 3 | 376 | 0.0034 | 0 |
| Pine Valley Creek[1] | 80 | 78 | 79 | 10 | NA | NA | NA |
| Rocky Creek | 68 | 58 | 48 | 8 | 298 | 0.0047 | 19 |
| Rogers Creek | 94 | 46 | 14 | 1 | 299 | 0.0047 | 0 |
| Shawnee Creek | 93 | 52 | 78 | 18 | 532 | 0.0033 | 0 |
| Sinking Creek | 90 | 326 | 53 | 6 | 734 | 0.0016 | 2 |
| Current River[2] | 56 | 5303 | 52 | 14 | NA | NA | NA |

[1] no reach-scale data collected because of difficulties with site access or a dry stream channel

[2] upstream of Ratcliff Ford

[3] upstream of Doniphan




Map of the Current River drainage basin showing study sites and public or conservation lands.

### Geology

Inventories of geology were based on digital version of state geologic maps at a scale of 1:500,000 (Missouri Department of Natural Resources, 1991; Hofer and others, 1995). GIS calculations involved summarizing data first by chronostratigraphic unit – the age and lithology based formations identified on the geologic maps – and second by regrouping these units into ones with similar lithologies. To compare effects of geology between study drainage basins of different sizes, all geology variables were calculated as proportions of drainage areas (table 4). Chronostratigraphic units were also grouped into six general lithologic categories based on stratigraphic descriptions from state geologic maps (Dean and others, 1979; Haley and others, 1993). Lithologic categories included: sandstone, interbedded sandstone and shale, shale, and carbonate in the Buffalo, and sandy carbonate, carbonate, and igneous rocks in the Current. The lithologic regrouping involved broad generalization because many formations contain interbedded lithologies or lateral facies changes. The only lithologic category present in both river system was carbonate, therefore it became the primary geologic variable in many analyses.

### Basin Physiography

Hydrologists have developed many variables to measure geometric and physiographic parameters of drainage basins. Typically these variables are used in regression equations to estimate discharge for ungaged streams (for example, Warner and others, 1996). For this study, five representative variables were selected, two to measure aspects of the planview geometry of the drainage basins and three to measure aspects of ruggedness or relief (table 4). Measurements were made from a 30-meter digital elevation model (DEM) made from tiled 1:24,000 quadrangles (USGS, 2000a).

The two planview physiographic variables selected were drainage area and drainage-basin shape. Drainage area was calculated using an ArcView script that modeled surface flow over the DEM and constructed drainage basin boundaries along drainage divides. Boundaries were compared and edited to match hypsography on 1:24,000-scale digital raster graphics (DRG) (USGS, 2000b). Each study drainage basin included the area upstream of the upper end of the study reach. In most cases, this site was within 2 km of the tributaries' confluence with the main-stem river. The second planview variable, drainage-basin shape, measured the narrowness of the drainage basins using the ratio of drainage-basin length squared to drainage area (table 4). This measure evaluates drainage-basin shape by comparing the area of the drainage basin to that of a square with sides equal to the drainage-basin length. Drainage-basin length was calculated by digitizing a line through the major stream valley, from the study reach to the drainage divide. The drainage-basin length line bisected the stream valley and therefore had a lower sinuosity than the stream itself.

Three variables measured aspects of drainage-basin relief including: elevation range, drainage-basin average slope, and bluff area within stream buffers (table 4). Elevation range was equal to the difference between the highest and lowest elevations in the study drainage basins. Drainage-basin average slope was calculated using ArcView Spatial Analyst (ESRI, 1998c) and the DEM. It calculated a slope for each grid cell by comparing the elevation in that cell to the surrounding eight cells. Drainage-basin average slope is the average of the slope measurements for all of the cells within the study drainage basin. A measure of streamside bluffs was also included as a relief variable since previous studies had suggested a relation between bluffs and stream geomorphology in the Ozarks (for example, Saucier, 1983; Jacobson, 1995; McKenney, 1997). We estimated the abundance of bluffs by calculating the area within stream buffers with slopes greater than 30 degrees (table 4). As with the calculations for drainage-basin average slope, the slope of each cell was calculated by comparing its elevation to the surrounding eight cells. Stream buffers were created from the EPA river-reach files (1:100,000-scale) and had graduated buffer widths based on the Strahler stream order of each stream segment. First order streams had a buffer width of 25 m and width increased by an additional 25 m for each sequential stream order. A maximum buffer width of 300 m was used for streams of orders six and greater.

### Land Use

Human use of the study drainage basins was evaluated in terms of five main criteria – three measures of anthropogenic land-cover types and two measures of road network density (table 4). Land-cover measurements were based on preliminary versions of the National Land Cover Data (NLCD), a nationwide data set developed by EROS Data Center (USGS, 2000b; Appendix 1). For this study we integrated many of the NLCD land-cover classes into one category called cleared land. This included NLCD categories for shrubland, transitional, herbaceous upland, or herbaceous cultivated. In general, areas of shrubland, transitional, and herbaceous cultivated lands were extremely sparse – they covered less than 1 percent of either the Buffalo or the Current drainage basins. Therefore, our cleared land category largely reflects lands classified as hay or pasture in the NLCD data set.

As with the geology variables, the five land use variables are all reported as proportions or as densities

**Table 4**. Drainage-basin variables, definitions, and data sources

[m, meters; $m^2$, square meters; $km^2$, square kilometers]

| Drainage-Basin Variables | Definition | Data Source |
|---|---|---|
| | **Geology** | |
| Formation area, as a proportion | Area of each chronstratigraphic unit summed and divided by *drainage area.* | 1:500,000-scale state geologic map of Missouri (MDNR, 1991; http://msdis.missouri.edu/html/sgeol.html) |
| Carbonate bedrock area, as a proportion | Formations regrouped by dominant lithology; area with carbonate bedrock summed and divided by *drainage area.* | modified 1:500,000-scale[1] state geologic map of Arkansas (Hofer and others, 1995) |
| | **Physiography** | |
| Drainage area ($m^2$ or $km^2$) | Total area upstream of upper end of study reach; drainage basin boundaries delineated using an ArcView Spatial Analyst Script (http://gis.esri.com/arcscripts/details.cfm?CFGRIDKEY=951497255) and refined by comparison with elevation contours on USGS 1:24,000 digital raster graphics. | |
| Drainage-basin shape factor | Basin length squared divided by *drainage area* where basin length is the total length of a line bisecting the major river valley, from the upper end of the study reach to the drainage divide. | 30-meter resolution digital elevation model, tiled from 1:24,000 USGS quadrangle sheets (USGS, 2000a; http://mapping.usgs.gov/mac/isb/pubs/factsheets/fs04000.html ) |
| Elevation range (m) | Highest minus lowest elevation in study drainage basin. | 1:24,000-scale digital raster graphics (USGS, 1999; http://mapping.usgs.gov/mac/isb/pubs/factsheets/fs07099.html ) |
| Drainage-basin average slope (degrees) | Average slope for all grid cells within a study drainage basin where slope is calculated by comparison of each cell's elevation to that of the surrounding eight cells. | |
| Bluff area in stream buffer, as a proportion | Area of cells with slopes greater than 30 degrees within a stream buffer, divided by the buffer area. Buffers had graduated widths based on the Strahler stream order. First order streams had a buffer width of 25 m on each side of the stream. Width increased by an additional 25 m for each sequential stream order up to a maximum of 300 m. | |
| | **Soils** | |
| No variables selected. | | 1:250,000-scale STATSGO soils coverage (USDA, 1994a, 1994b; http://www.ftw.nrcs.usda.gov/stat_data.html ) |

[1] Map was tiled from 1:24,000-scale and coarser resolution data. Cells were reclassified to match geologic categories on the statewide 1:500,000-scale geologic by Haley and others (1993).

**Table 4**. Drainage-basin variables, definitions, and data sources--Continued

| Drainage-Basin Variables | Definition | Data Source |
|---|---|---|
| | **Stream Network** | |
| No variables selected. | | 1:100,000-scale rf3 river reach files (USEPA, 1998; http://www.epa.gov/owowwtr1/monitoring/rf/rfindex.html ) |
| | **Land Cover** | |
| Cleared land area, as a proportion | Sum of area classified as developed, shrubland, transitional, herbaceous upland, or herbaceous cultivated (NLCD categories 33,51,71,81,82,83,84,85), divided by *drainage area.* | 30-meter resolution National Land Cover Data (NLCD) (USGS, 2000b; http://edcsgs9.cr.usgs.gov/programs/lccp/nationallandcover.html ). Coverage for the state of Arkansas was based on Landsat Thematic Mapper (TM) scenes taken from April 1988 through December 1993. Coverage for the state of Missouri was based on scenes taken from March 1988 through October 1993 (see Appendix 1 for more details). |
| Steep, cleared land area, as a proportion | Cleared land area on slopes greater than seven degrees divided by *drainage area* (calculated by reclassifying and merging NLCD and slope grids). | |
| Cleared land area in stream buffer, as a proportion | Cleared land area within stream buffers divided by total *drainage area*. See definition of *bluff area* for buffer explanation. | |
| | **Road Network** | |
| Road density ($m/m^2$) | Total road length within a basin divided by *drainage area*. | 1:100,000-scale TIGER/Line files (USCB, 1992; http://www.census.gov/mp/www/rom/msrom12f.html ) |
| Road density in stream buffer ($m/m^2$) | Total road length within a stream buffer divided by buffer area. See definition of *bluff area* for buffer explanation. | |
| | **Stewardship and Political** | |
| Private land area, as a proportion | Area outside of state, federal, or Nature Conservancy land management areas divided by *drainage area.* | 1:100,000-scale stewardship boundaries (CAST, 1998; http://www.cast.uark.edu/gap/ ) (MORAP, 1997; http://www.cerc.cr.usgs.gov/morap/projects/publand/stewardship.htm ) |
| Cities and towns on reference maps. | | 1:2,000,000-scale city and town locations from the National Atlas (USGS, 2000c; http://www.nationalatlas.gov/atlasftp.html ) |

so that comparisons could be made between drainage basins of different sizes (table 4). Cleared land area was also measured for specific landscape positions in order to investigate the effects of land clearing near streams or in settings more likely to be sensitive to erosion. These included steep, cleared land area (the proportion of the drainage basin with cleared land on slopes greater than 7 degrees) and cleared land area within stream buffers. Road density was measured for both the study drainage basins as a whole and within stream buffers by dividing total road length by area. The stream-buffer road density variable was introduced to measure the greater disturbance potential of roads near or within streambeds (table 1).

## Reach-Scale Data Collection

Field inventories of habitat characteristics were carried out in 36 tributaries during the summer of 1999. The inventory included: measurements of channel geometry and habitat types, measurements of substrate characteristics, and indicators of channel instability. Reaches were chosen on the tributaries near their junctions with the main stem. To avoid backwater effects, the elevation of a reach's downstream endpoint was above the elevation of bankfull indicators on the main-stem channel.

We stratified measurements in three locations throughout the reach: along a thalweg longitudinal profile, along cross sections in glide habitats, and on point bars (fig. 5). Field protocols drew upon methods developed for other national and local monitoring programs including the USGS National Water-Quality Assessment Program (Fitzpatrick and others, 1998; Femmer, 1997) and U.S. Environmental Protection Agency protocols (MacDonald and others, 1991). The protocols developed for this study were also informed by previous studies of Ozarks streams (Jacobson, 1995; Jacobson and Pugh, 1999; Jacobson and Primm, 1997; McKenney, 1997; McKenney and Jacobson, 1996; Rabeni and Jacobson, 1993; Doisy and Rabeni, in press; Peterson, 1996) and focused resources on stream characteristics that were suspected to be sensitive to landscape disturbances in the Ozarks. Appendix 2 contains detailed field instructions and an example field data sheet.

The thalweg longitudinal profile was surveyed with a laser theodolite through a minimum of three riffle-pool sequences or a distance of at least 20 bankfull channel widths (fig. 5; table 5). The profile was made up of a series of points measured 3 to 10 meters apart. At each point, we surveyed water-surface and bed elevations and used a data logger to recorded information about thalweg habitat type, dominant substrate particle size, substrate embeddedness, percent of banks covered by vegetation or bedrock, and bank erosion. Habitat types were identified using a qualitative classification scheme that took into account flow depth, flow velocity, channel geometry, and substrate (fig. 6). A floating, foam-edged Plexiglas square was used as a "window" to break the water-surface and view substrate. Particle size and embeddedness were reported for a one-meter diameter circle around the base of the surveyor's stadia rod.

On return from the field, data collected along the longitudinal profile was reduced into the geomorphic and habitat parameters listed in table 5. Measurements of habitat, substrate, and bank conditions were integrated over the study reach using a distance-based averaging method. The reach distance was divided into segments based on survey point locations, and then observations from each survey point were applied to that section. For example, the proportion of cobble substrate along the thalweg was equal to the sum of segments with cobbles divided by the total reach length. The same procedure was used to calculate other length-based proportions, such as the proportion of eroding banks and the proportion of each habitat type.

A similar procedure was used to calculate an index of thalweg embeddedness and of bank vegetation cover (table 5). In both cases, visual estimates at each survey point were made as a proportion (for example, 10 percent embedded or 50 percent of banks vegetated). The total length of segments with each proportion was summed and multiplied by the proportion of embeddedness or cover. These numbers were then summed to determine an embeddedness or bank vegetation index for the reach. In the case of stream banks, estimates were for right and left banks, therefore indexes were summed and divided by two.

Measurements of residual pool geometry also were calculated from the thalweg survey data (fig. 5). Residual pools were constructed from survey data by extending the elevation of each riffle crest upstream until it intersected the channel bed. The length of this line was the residual pool length (table 5). The proportion of residual pools within a reach was calculated by summing the total length of residual pools and dividing by the reach length. This variable contrasts with average residual pool length, which was the total length of residual pools divided by the number of pools.

Average residual pool depth was calculated using a method similar to that used to determine average cross-sectional channel depth for stream discharge measurements (Rantz, 1982). A depth was calculated for each survey point along the longitudinal profile as the difference between the stream bed elevation at that point and the elevation of the downstream riffle crest. This depth was then applied to the thalweg segment

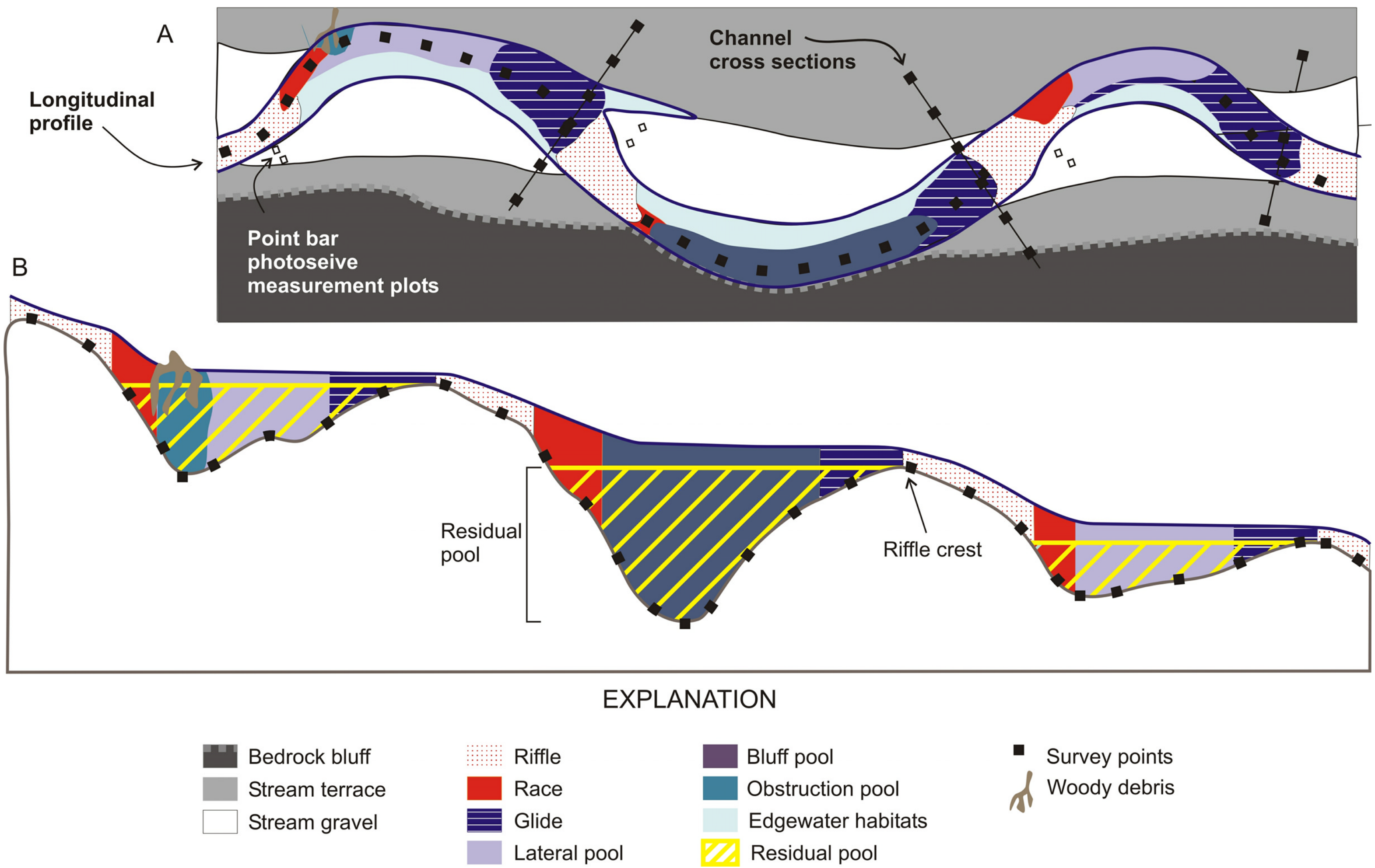



**Figure 5.** Sketches illustrating field survey measurements and the typical distribution of thalweg habitats: A. planview and B. along the longitudinal profile (with vertical exaggeration). Measurements were taken along the longitudinal profile, on cross sections through glide habitats, and on point bars.

High gradient

**Riffles**

shallow, trapezoidal cross sections, flow is divergent and turbulent; riffles usually have the coarsest substrate within the reach

**Races**

V shaped cross sections, races typically form at the downstream end of riffles where flow converges and deepens; substrate is variable

Low gradient

**Glides**

trapezoidal cross sections, flow is diffuse often lacking a distinct thalweg; glides are usually present upstream of riffles where the channel bed slopes upward toward the riffle crest, sometimes they also occur downstream of riffles in straight channel segments; substrate is variable

**Pools**

**Lateral pools**

asymmetric cross sections, lateral pools usually form along the outside bank in a meander bend; substrate is variable

**Bluff pools**

asymmetric cross sections, at low discharges there may be negligible velocity; bluff pools are similar to lateral pools but form where bedrock makes up the outside bank in a meander bend; bluff pools tend to be the deepest habitats within the reach and often have bedrock or boulder substrate

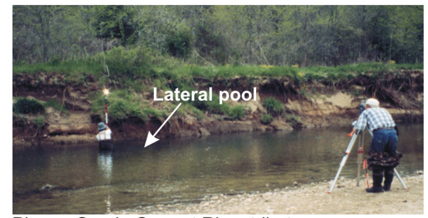
**Mid-channel pools**

symmetric, V-shaped cross sections, at low discharges there may be negligible velocity; mid-channel pools sometimes form in the troughs between wave-like gravel mounds; substrate is variable

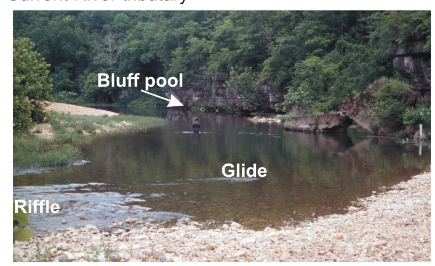
**Obstruction pools**

irregular cross sections, obstruction pools usually form behind large woody debris or boulders; substrate is variable

Big Creek (upper), Buffalo River tributary

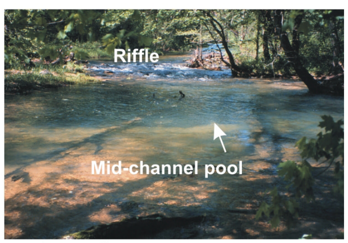


Pigeon Creek, Current River tributary



Jacks Fork, Current River tributary

Big Creek (east), Current River tributary



Mill Creek, Current River tributary

**Figure 6.** Descriptions and photographs of the thalweg habitat units mapped in field surveys. Classification system was modified from McKenney (1997).

**Table 5**. Reach-scale variables, definitions, and measurement techniques

| Reach Scale Variable | Definition | Measurement Technique |
|---|---|---|
| | **Channel Geometry** | |
| Reach gradient | Slope of a best-fit line through water surface points surveyed along the thalweg. | |
| Total residual pool length (m) | Total length of reach within residual pools. | |
| Residual pools, as a proportion | *Total residual pool length* divided by total reach length. | Calculated from the geometry of the longitudinal profile survey, see Figure 5. |
| Average residual pool length (m) | *Total residual pool length* divided by the number of residual pools. | |
| Average residual pool depth (m) | Residual pool area (measured along longitudinal profile) divided by *total residual pool length.* | |
| Pools, as a proportion of reach length | Rotal reach length classified as lateral, bluff, mid-channel or obstruction pools divided by total reach length. | |
| Glides, as a proportion of reach length | Total reach length classified as glides divided by total reach length. | Calculated from visual identifications of habitat type made at each survey point along the longitudinal profile. See Figure 6 for habitat classification criteria. |
| Obstruction pools, as a proportion of reach length | Total reach length classified as obstruction pools divided by total reach length classified as pools. | |
| Average bankfull channel width (m) | Total distance across channel at bankfull elevation; average from 3-6 cross sections. | Calculated from the geometry of surveyed cross sections. Bankfull elevation was projected into cross sections from indicators identified throughout the study reach. |
| Average bankfull channel depth (m) | Bankfull channel area divided by *bankfull channel width*; average from 3-6 cross sections. | |
| | **Substrate** | |
| Mud/sand along thalweg, as a proportion of reach length | Dominant particle size <2 mm; total reach length classified as mud/sand divided by total reach length. | Calculated from visual estimates of dominant particle size and embeddedness at each survey point along the longitudinal profile. Estimate made within a one meter diameter circle around the base of the surveyor's stadia rod. Embeddedness reported as the proportion of the circle covered with mud or sand, in intervals of 0.1. |
| Gravel along thalweg, as a proportion of reach length | Dominant particle size 2-64 mm; total reach length classified as gravel divided by total reach length. | |
| Cobbles and boulders along thalweg, as a proportion of reach length | Dominant particle size >64 mm; total reach length classified as cobbles/boulders divided by total reach length. | |

**Table 5**. Reach-scale variables measured in field surveys--Continued

| Reach Scale Variable | Definition | Measurement Technique |
|---|---|---|
| | **Substrate--Continued** | |
| Thalweg embeddedness index | Summation of embeddedness class times the proportion of reach length within each embeddedness class. | |
| Glide D16 (mm) | $16^{th}$ percentile of particle size distribution; average from three glides. | |
| Glide D50 (mm) | $50^{th}$ percentile of particle size distribution; average from three glides. | |
| Glide D84 (mm) | $84^{th}$ percentile of particle size distribution; average from three glides. | Calculated from cumulative particle size distributions from pebble counts of 100 particles. |
| Glide sorting (phi) | (D84 – D16)/4 + (D95-D5)/6); where particle sizes were transformed to phi ($-\log_2$(diameter, mm)) and D84, D16, D95, and D5 are equal to $84^{th}$ , $16^{th}$, $95^{th}$, and $5^{th}$ percentiles of particle size distribution in glides. | |
| Glide embeddedness, as a proportion | Average of embeddedness from two locations in each of three glides. | The proportion of a 60 cm quadrant covered with mud or sand, reported in intervals of 0.05. |
| Point bar D16 (mm) | $16^{th}$ percentile of particle size distribution; average from two measurements on each of three point bars. | |
| Point bar D50 (mm) | $50^{th}$ percentile of particle size distribution; average from two measurements on each of three point bars. | |
| Point bar D84 (mm) | $84^{th}$ percentile of particle size distribution; average from two measurements on each of three point bars. | Calculated from particle size distribution from photoseive process (see Figure 7). |
| Point bar sorting (phi) | (D84 – D16)/4 + (D95-D5)/6); where particle sizes were transformed to phi ($-\log_2$(diameter, in mm)) and D84, D16, D95, and D5 are equal to $84^{th}$ , $16^{th}$, $95^{th}$, and $5^{th}$ percentiles of particle size distribution in glides. | |

**Table 5**. Reach-scale variables measured in field surveys--Continued

| Reach Scale Variable | Definition | Measurement Technique |
|---|---|---|
| | **Channel Stability** | |
| Bank vegetation index | Summation of vegetation class times the proportion of reach length within each embeddedness class; average of left and right banks. | |
| Severely eroding banks, as a proportion of reach length | Total reach length classified as severely eroding divided by total reach length; average of left and right banks. | Calculated from visual estimates made at each survey point along the longitudinal profile. Observations made of vertical banks below bankfull elevation. |
| Moderately and severely eroding banks, as a proportion of reach length | Total reach length classified as moderately or severely eroding divided by total reach length; average of left and right banks. | |
| Reach sinuosity | Total reach length divided by straight line distance between endpoints. | Calculated from planview of longitudinal profile survey. |
| Glide canopy cover | Average from densiometer readings at both ends of 3-6 cross sections. | Calculated from concave spherical densiometer readings near water's edge on each cross section. Methodology followed Fitzpatrick and others (1998). |

around this point. Long-section residual pool area was calculated for each thalweg segment, summed for the whole reach, and divided by total residual pool length to determine a weighted average of residual pool depth. One of the advantages of residual pool measurements is that they are not influenced by discharge as many other depth based habitat classes are.

Channel cross sections were surveyed with the total station in three glide habitats (fig. 5). We concentrated these measurements within a single habitat type to reduce within-reach variability. Cross-section measurements were used to determine bankfull channel geometries – bankfull is thought to be indicative of the "channel forming flow", a flood with a recurrence interval of about 1.5 to 2 years (Leopold and Maddock, 1953). Indicators of bankfull elevation were identified and surveyed along the longitudinal profile using criteria outlined by Fitzpatrick and others (1998). Generally, we found the most internally consistent indicators to be at the apex of point bars where bare gravel substrate transitioned into sandy substrate and perennial vegetation. Frequently, this change in substrate and vegetation occurred at a topographic break in slope. The flat surface of the point bar transitioned into a more steeply sloping terrace riser. At the site of the stream gage on the Buffalo River at St. Joe (fig. 3), the elevation of the point bar apex corresponded to a flow with a recurrence interval of 1.4 years (M. Maner, Arkansas Department of Environmental Quality, written communication, 1999).

On return from the field, surveyed indicators of bankfull elevation were plotted along the longitudinal profile and used to interpolate a bankfull water surface elevation. Elevations from this line were used to calculate bankfull geometry in glide cross sections. Bankfull width was equal to the length of a horizontal line across the channel at bankfull elevation. Average bankfull depth was calculated using the same established procedures for calculating stream discharge (Rantz, 1982). Cross sections were broken into segments on the basis of survey point locations, and then channel cross sectional area was calculated for each segment and summed. Average bankfull depth was calculated as cross-sectional area divided by bankfull channel width. Average reach bankfull depth, width, and area were calculated from three to six cross sections in each study reach.

Substrate characteristics and canopy cover were also measured at each cross section. Particle size was estimated using Wolman pebble counts (Wolman, 1954), embeddedness was estimated visually, and canopy cover was measured using a densiometer. The procedure for pebble counts included making 100 "blind" touches to the stream-bed and picking up the first particle touched. The particle was then measured using calipers, or if too large, using an engineer's ruler. Glide substrate measurements are reported in millimeters for 16th, 50th, and 84th percentile from the 100 particles measured in each glide (table 5). The numbers reported are averages from the three pebble counts conducted in each reach. Embeddedness in glides was estimated using a 60x60 cm floating Plexiglas quadrant. Within the square, we visually estimated the percent sand and mud particles surrounding or covering coarser substrate by making comparisons with illustrations of known embeddedness fractions. We measured canopy cover at each cross section using a concave sperical densiometer and the method outlined in Fitzpatrick and others (1998, table 5).

We measured substrate on point bars in an additional way, by photosieving (Adams, 1979; Ibbeken and Schleyer, 1986, fig. 7). Using a tripod and a 40x60 cm quadrant, we photographed the bar surface material at two locations on each of three point bars. To sample in a hydraulically similar location, all photos were taken at a standard position on the bar – at the upstream end,

A

B

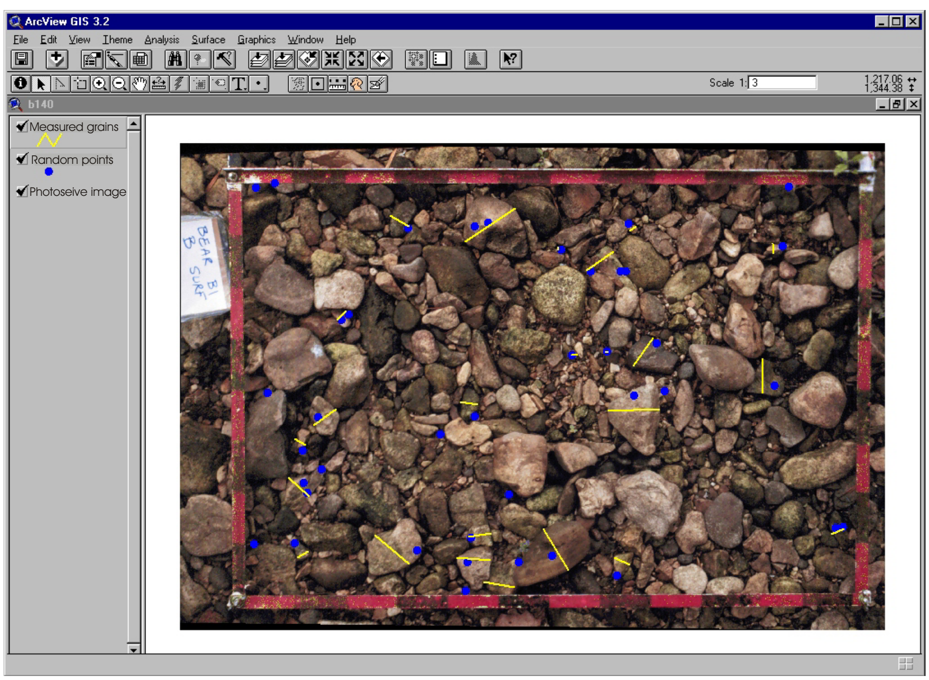



**Figure 7.** Illustration of the photosieve method. A. Photographs were taken on point bars using a tripod and quadrant. B. Once scanned, the photograph was registered and rectified using the quadrant and particle size was measured on screen for randomly selected particles.

equally spaced across the point bar along a line bisecting the adjacent riffle (fig. 5). On return from the field, photographs were scanned, rectified in Arc/Info, and loaded into ArcView. Using an ArcView script we generated a shapefile with randomly scattered points across the photograph. We then used the online measuring tools to measure the apparent median axis of rocks identified by the random dots. A second script recorded those measurements automatically into a data file.

We measured 31 rocks in each photograph, a number determined by estimating the variance for the population. The number of random points (31) was determined using a standard sample size formula (Thompson, 1992). This sample size allowed us to be 95 percent confident that we could estimate particle size in phi[4] to within 0.5 units of the true value. The sample size formula depends on the population variance, which was unknown. We therefore substituted the sample variance from 150 clast measurements taken from 30 randomly selected photographs (5 random clasts per photograph).

In total, photoseive measurements were completed on 144 photographs from 25 stream reaches. Sites were excluded from photosieving when particle size was too large to obtain a representative sample within the measuring quadrant. Because only two dimensions of particles are visible in photographs, photosieve measurements are not directly comparable to particle sizes measured in other manners such as pebble counts or sieving. Instead, they should be viewed as a relative measure of differences in particle size between the tributaries.

## Segment-Scale Data Collection

To develop a synoptic overview of gravel in transport in the Current and Buffalo River basins, a longitudinal inventory of gravel-bar area was developed for 180 km of the Current River main stem and 247 km of the Buffalo River by mapping from low-altitude aerial photographs (fig. 8). The photographs were scanned and georeferenced according to photo-identifiable points with known positions, and gravel deposits were mapped in Arc/Info using automated image-processing classification and visual identification based on ranges of color intensity. Because of the great contrast between light-colored gravel bars and adjacent vegetation and rock, this method proved simple and accurate.

Dates and discharges during periods of aerial photography are given in table 6. All photographs were taken

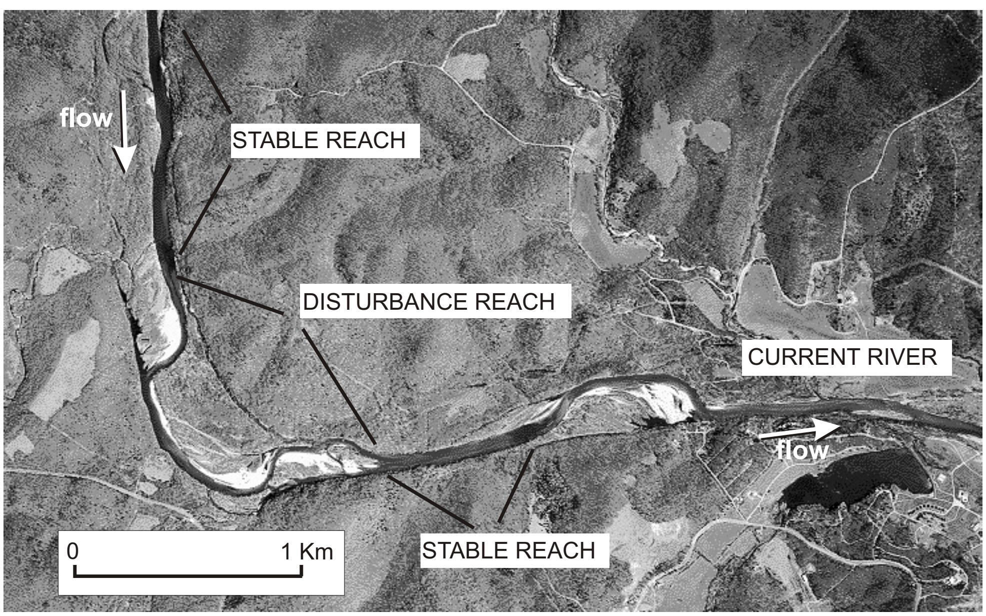



**Figure 8.** Aerial photograph showing a typical segment of the Current River and juxtaposed stable and disturbance reaches.

[4] Phi is a logarithmic transformation of particle size in which the negative logarithm to the base 2 of the particle diameter (in millimeters) is substituted for the diameter value (Krumbein, 1934).

**Table 6**. Dates and discharges for aerial photography
[$m^3/s$, cubic meters per second; NA, not available]

| Date | Discharge ($m^3/s$) | Ratio to Mean Annual Discharge (percent) | Discharge ($m^3/s$) | Ratio to Mean Annual Discharge (percent) | Discharge ($m^3/s$) | Ratio to Mean Annual Discharge (percent) |
|---|---|---|---|---|---|---|
| | **Jacks Fork at Eminence** | | **Current River at Van Buren** | | **Current River at Doniphan** | |
| 3/8/92 | 11.4 | 86.9 | 51.8 | 91.6 | 63.4 | 79.9 |
| 4/16/96 | 18.9 | 143.9 | 65.7 | 116.2 | 90.6 | 114.1 |
| | **Buffalo River near Boxley** | | **Buffalo River near St. Joe** | | | |
| 3/1/00 | 2.8 | NA | 27.5 | 91.4 | | |
| 3/27/00 | 4.2 | NA | 15.8 | 52.5 | | |

during leaves-off periods. Varying discharges between dates of photography or varying flow exceedence along the river can potentially confuse this analysis. Hydrographs for relevant periods from four gages on the Current River are shown in figure 9. Hydrographs 1992 – 1996 (figs. 9A, B) show the recent history of flood events on the river that could affect the interpretation of the longitudinal distributions of gravel determined from aerial photography on specific dates. To normalize for differences in discharge between the two dates of photography on the Current River, gravel inventories have been expressed as percentages of the total bar area measured during each date. Detailed hydrographs for Current River at Van Buren, Missouri and Current River at Doniphan, Missouri just before and after the photography dates suggest that only slight flood waves may have been present on the river (fig. 9C, 9D). Stage-width relations derived from discharge measurement data for these two gages indicate that expected variation in wetted channel width over the range of prevailing discharge would be relatively small, perhaps on the order of 5 percent (fig. 10), indicating that gravel bar inventories may have a maximum of this amount of error due to the longitudinal variation in flow.

Photography on the Buffalo River was acquired on two separate dates during March 2000. The hydrographs 1996 – 2000 (fig. 11A) show the hydrologic context of the years preceding aerial photography acquisition and the extremely low base flow periods that characterize Buffalo River hydrology. Detailed hydrographs for the Buffalo River at Boxley, Arkansas and St. Joe, Arkansas, document relatively steady and equivalent discharges during this time period (fig. 11B). Stage-width relations from the gage near St. Joe indicate that average wetted width varies little at the prevailing range of discharges, although there is substantial variation among discharge measurements (fig. 12).

The distribution of gravel along the river was inventoried by defining address points at 200-m intervals along a digital representation of the centerline of the main-stem channel (fig. 13). Gravel areas were assigned to each address point by intersecting circular areas of 125 m radius centered at each address point with the mapped gravel bars. This method ensures that most gravel along the channel is inventoried, but oversamples slightly in reaches where gravel bars are close together. The addressing system allows channel, valley, and basin characteristics to be associated with each point on the main stem, thereby allowing a nearly continuous evaluation of factors that potentially affect channel dynamics.

The utility of gravel-bar area as a measure of gravel in transport through the river system is based on two assumptions: that bare gravel mapped in bars is in active transport over relevant time frames and that gravel-bar area is a useful index of gravel volume. Monitoring of channel morphological change on the Jacks Fork (Current River tributary) and Buffalo River (McKenney and Jacobson, 1996) and regional analysis of streambed elevation changes (Jacobson, 1995) confirm high rates of exchange of gravel between channel and bars, and generally high bedload transport rates of Ozarks streams. The volume of gravel in transport is underestimated by a factor equal to the thickness of the gravel bar. To the extent that gravel thickness is constant or proportional to bar area, the longitudinal trends in bar area will underestimate volume but still show valid longitudinal patterns. If gravel thickness decreases while area increases, then area inventories would not be a valid measure of longitudinal variation in sediment volume. Although quantitative data on gravel bar thicknesses are lacking, field observations along the Current River have not indicated a decrease in bar thickness with an increase in bar area, or the presence of hydraulic or geologic controls that would produce anomalously thin bars.

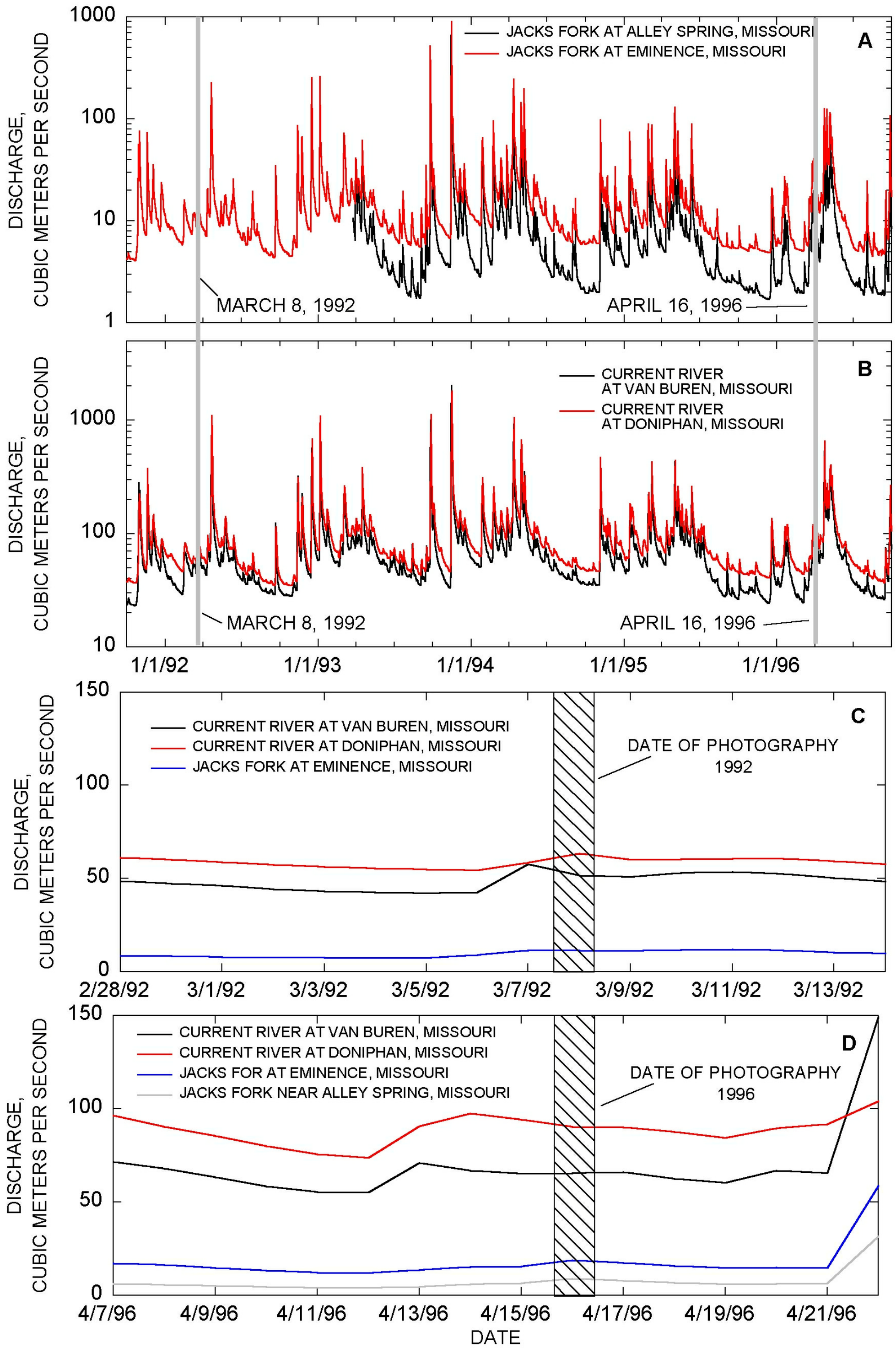
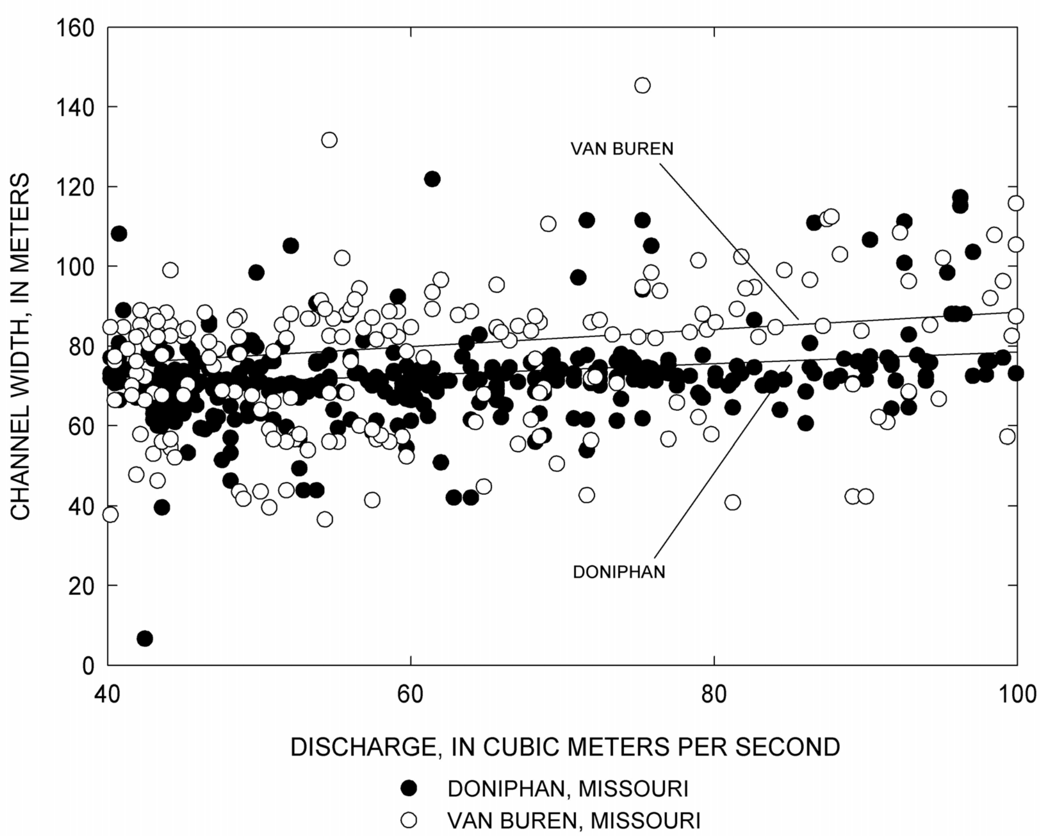



**Figure 9.** A. Hydrographs, Jacks Fork near Alley Spring, Missouri and Jacks Fork near Eminence, Missouri, and dates of aerial photography. B. Hydrographs, Current River at Van Buren, Missouri and Current River at Doniphan, Missouri, and dates of aerial photography. C. Detailed hydrographs before, during, and after aerial photography, 1992, for sites on the Current River and Jacks Fork. D. Detailed hydrographs before, during, and after aerial photography, 1996, for sites on the Current River and Jacks Fork.

Analysis of causal factors that might affect the longitudinal distribution of gravel in these rivers potentially is confounded by systematic upstream-downstream trends in gravel-bar areas. All other factors being equal, we would expect gravel-bar area to increase naturally in the downstream direction as a function of increasing drainage area and increasing channel size. To normalize for this trend, we assumed that in a non-disturbed system, gravel-bar area would be directly proportional to channel size. Further, we used the conventional assumption that channel width is adjusted systematically to the bankfull discharge, usually a 1.5-2 year flood (Leopold and Maddock, 1953) and regional flood-frequency relations for the 2-year flood (Alexander and Wilson, 1995; Hodge and Tasker, 1995) to estimate how bankfull channel width should vary with drainage area along the river main stems. This required adoption of a relation between bankfull discharge (determined from drainage area above each main-stem address point) and channel width based on conventional channel geometry relations (Leopold and Maddock, 1953). In this relation, bankfull channel width is given as a power function of discharge with constants for the power and linear coefficients. We used a power coefficient of 0.5 as suggested by Leopold (1994) and a linear coefficient of 1. The actual value of the linear coefficient is not important because the normalization is based on the shape of longitudinal relation, not on an actual estimate of channel width (fig. 14). The normalization value yields an estimated channel width in meters.

Exploration of the links between tributary basin characteristics and gravel-bar inventory require a summation of gravel-bar area over some length downstream from tributary junctions. The question is how far downstream would we expect gravel-bar area to be correlated with geologic, physiographic, or land-use characteristics of the tributary basins. Because we have little understanding of how far pulses of gravel delivered to the mainstreams might translate or disperse downstream, we calculated areas summed over arbitrary distances of 0.2, 0.4, 0.6, 1.0, 1.6, 2.0, 2.6, 3.0, 3.6, and 4.8 km downstream from tributary junctions to serve as response variables for exploratory purposes.




Relation between width and discharge, Current River at Van Buren, and at Doniphan for discharges

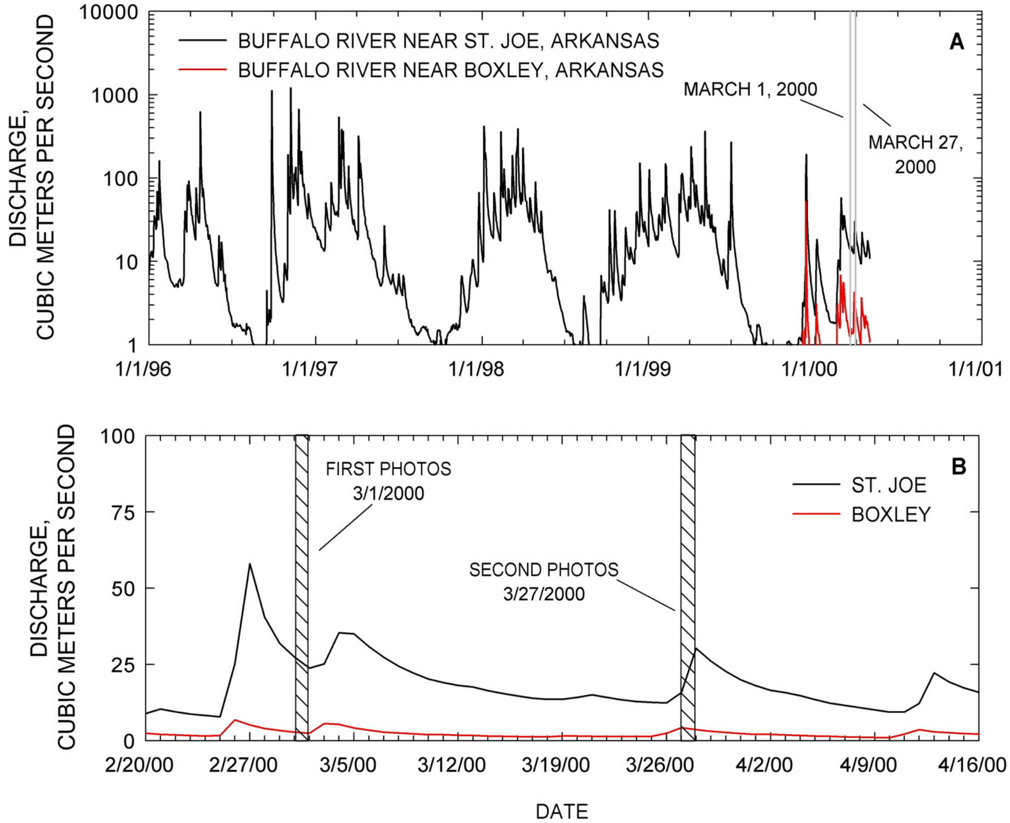


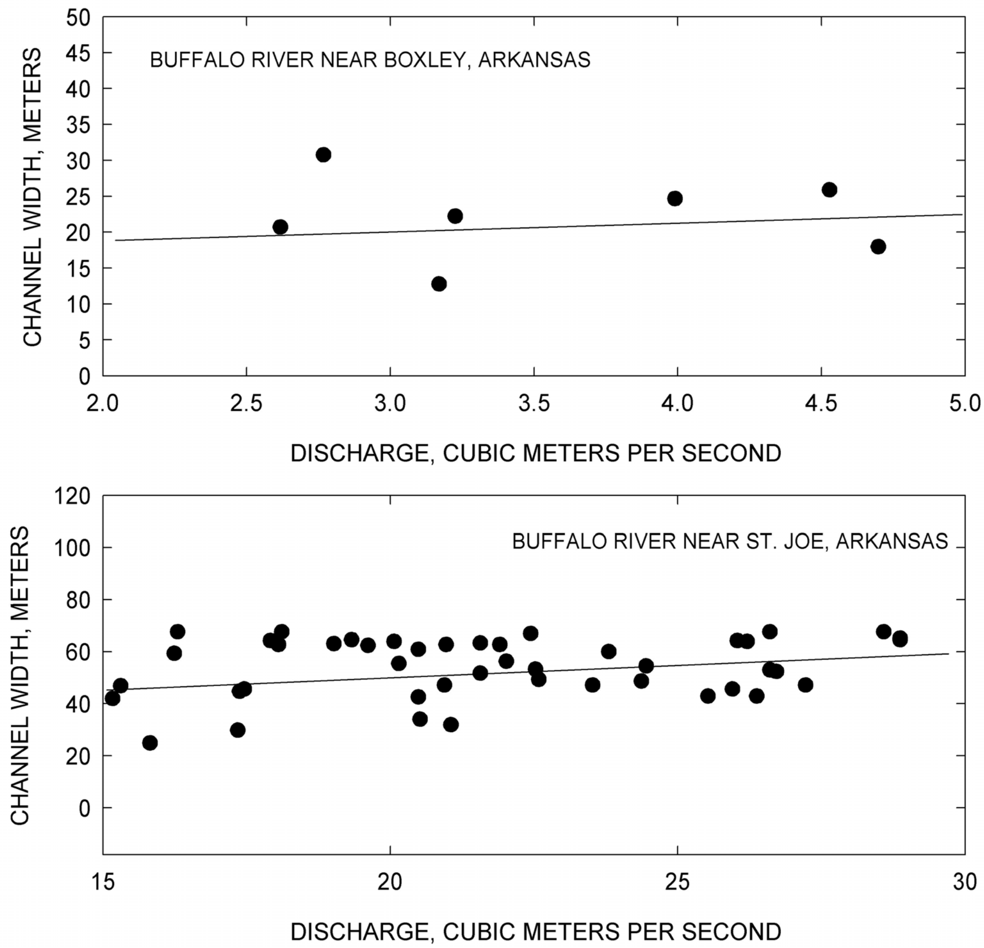

**Figure 11.** A. Hydrographs, Buffalo River near Boxley, Arkansas, and Buffalo River near St. Joe, Arkansas 1996 - 2000. B. Detailed hydrographs in March 2000 and two dates of aerial photography.

## Statistical Analyses

Data analysis employed an exploratory approach and three statistical techniques: correlation analysis, multiple regression, and principal components analysis. The SAS statistical software package, version 8 (SAS Institute, Inc., 1999) was used for all statistical analyses.

We used correlation analysis and scatter plots to investigate bivariate relations between variables. Scatter plots indicated non-linear relations between some variables, therefore we used Spearman rank correlations (for example, SAS, 1999) to quantify the strength of bivariate relations. Data tables in this report highlight correlation coefficients that were significant at $p \leq 0.05$. Correlation analyses helped identify related variables within a scale and identify relations between scales. For example, correlation analysis highlighted relations between different measurements of channel geometry and between channel geometry variables and drainage-basin variables. Comparisons of correlation coefficients for all study drainage basins grouped together and separated into Buffalo and Current River groups also helped identify differences between the two river systems.

Based on correlation analysis, we selected specific relations to investigate further with multiple regression. This technique allowed us to assess whether these relations persisted after adjusting for other explanatory variables. The assumptions of multiple linear regression were assessed using scatter and residual plots (Ramsey and Schafer, 1996). Data were transformed when necessary to meet these assumptions; transformations are noted in tables of regression models. All explanatory variables in the models presented were significant at $p \leq 0.05$. Multiple regression was an important tool in this study because in many cases the relation with one explanatory variable needed to be accounted for before a relation with another explanatory variable could be resolved. For example, channel dimensions varied with drainage area – larger drainage basins had larger channels. Multiple regression allowed assessment of the relation between channel dimensions and other drainage-basin variables, such as cleared land area, after accounting for differences in drainage area. This report uses partial residual plots to graphically




Relations between width and discharge Buffalo River near Boxley, Arkansas, and Buffalo River

present data from multiple regression. These plots help show the relation between one explanatory variable and the response variable after removing the influence of another explanatory variable. Partial residual plots were calculated using the method outlined by Ramsey and Schafer (1996).

In using multiple regression, our goal was not to develop predictive models but rather to explore the relative influence of different drainage-basin characteristics on tributaries of the Buffalo and Current Rivers. Our approach was to develop a series of multiple regression models for a set of related response variables and look for consistency within the set of models. For example, we developed separate models for many measures of channel geometry (e.g. bankfull width and depth, residual pool length and depth). In interpretation, we then placed the most emphasis on explanatory variables that were consistently significant for many of the response variables. For example, we might conclude that drainage-basin area and drainage-basin average slope are important explanatory variables for measures of channel geometry if they consistently appeared in multiple regression models for many different channel geometry variables.

For the drainage-basin analyses, we also used principal components analysis (PCA) to gain an understanding of the variability within the data sets and identify differences between the two river systems, Buffalo and Current. PCA is an exploratory multivariate technique that determines the linear combination of variables that best explains the variation within a data set (for example, Ramsey and Schafer, 1996). When site scores were plotted on axes representing the principal components, the data often clustered into groups that helped identify sites with similar characteristics. For example, we used PCA to help recognize similarities between land use patterns in the study drainage basins.

## Results: Tributary Drainage-basin Characteristics

This section presents findings from the basin-scale GIS analyses. It describes the characteristics of the Buffalo and Current River systems, makes comparisons between tributary drainage basins, and discusses relations between basin-scale variables. In so doing it provides the landscape-scale context that is fundamental for understanding anthropogenic impacts on streams in the Ozarks.

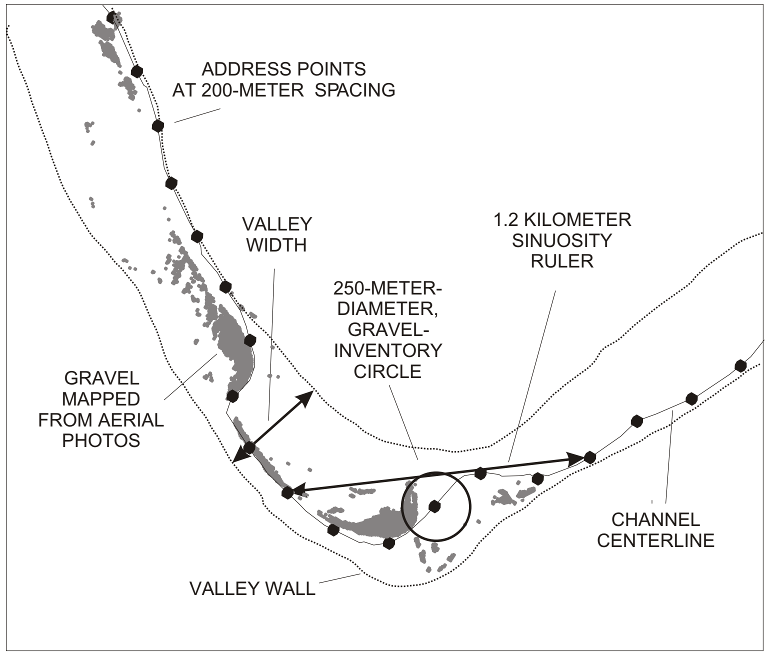



**Figure 13.** Map showing a typical portion of the Current River valley, address points, gravel-bar area, and various measurements.

### Geology

#### Current River System

The Current drainage basin is underlain primarily by carbonate with interbedded chert and sandstone. Most of the geologic sequence dates to between the Cambrian and Ordovician (570-438 million years ago) and includes the Potosi, Eminence, Gasconade, and Roubidoux Formations (Figures 15-16; MDNR, 1991). Scattered knobs of Proterozoic (~1500 million years old) volcanic rock related to the St. Francis Mountains underlie this sequence (fig. 15). In places, the sedimentary rocks drape over the igneous knobs, and geologists believe the knobs formed islands in the ancient Ordovician seaway (Orndorff and others, 1999). Even though the igneous rocks are not extensive, they have an important effect on topography and perhaps also on hydrology in the Current River drainage basin. They are resistant to erosion and create many of the topographic highs in the landscape today, including Stegall, Coot, and Shut-in Mountains (fig. 15). They are also highly impermeable and many of the creeks that drain these uplands have sustained baseflows that are remarkable in a region with many underdrained streams[5]. Rocky, Mill, and Rogers Creeks (fig. 15),

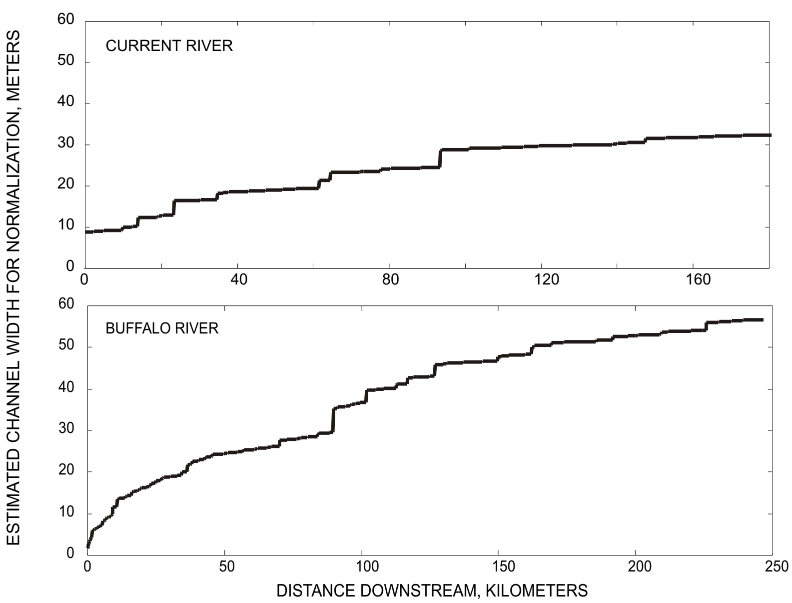



**Figure 14.** Relation between estimated channel width normalization factor and distance downstream, Current River and Buffalo River.

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[5] We use the word underdrained to describe streams that are affected by karst hydrology. They may be dry for most or part of the year or contain sections of losing stream. We consider them to be a subset of ephemeral or intermittent streams – the broader category that includes streams that flow for part of the year due to climatic or geologic factors unrelated to karst hydrology.

three tributaries which drain Coot Mountain, maintained steady baseflows even during periods with extremely low rainfall between July 1999-July 2000. In contrast to the igneous rocks, the dolomites are much more easily eroded and dissolved. Their weathering is what produces the region's karst hydrology with its famous springs, extensive cave networks, and sinkhole-pocked landscape.

Generally, there is a down-section shift moving from west to east in the Current River system, following the drainage basin's topography (fig. 15). Western and northern tributary drainage basins have the highest elevations and drain the flat lying uplands of the Salem Plateau. The Jefferson City Dolomite underlies their upper regions; this is the cherty carbonate that caps the regional geologic sequence (fig. 16). Beneath the Jefferson City Dolomite, lies the Roubidoux Formation, a unit with many sandstone beds. This formation underlies the middle portion of many western tributary drainage basins and forms ridges throughout the drainage basin; its sandy, well-cemented texture makes it the most resistant sedimentary rock type in the area. Beneath the Roubidoux Formation is the Gasconade Dolomite, another carbonate unit that is susceptible also to dissolution. It forms the valley bottoms in the western tributaries – valleys that in many cases hold underdrained streams, a characteristic that may relate to the cave horizon found in the upper part of the formation (R. Harrison, research geologist, U.S. Geological Survey, Reston, VA, oral communication, July 2000). Examples of west Current underdrained streams include some of the largest tributary drainage basins in the river system – Big Creek (west), Spring Valley Creek, and Pike Creek.

Elevations are generally lower in the eastern and middle Current and the tributary drainage basins are dominated by older geologic formations. The Roubidoux Formation is found generally in small amounts capping ridges, while the Gasconade Dolomite is more extensive and underlies heavily dissected uplands and steep hillslopes. Valley bottoms are made dominantly of the Eminence and Potosi Formations. In many of the middle Current drainage basins, the Proterozoic igneous rocks also crop out. Although they make up less than 1 percent of the entire Current River system, they make up 25 percent of Rocky Creek's drainage basin and lesser amounts of Rogers, Mill, Blair, and Shawnee drainage basins (fig. 15).

**Buffalo River System**

In the Buffalo drainage basin, the stratigraphic sequence is younger (Ordovician to Pennsylvanian) and includes more sandstone and shale and less carbonate. However, similar to the Current, rock formations become older moving toward the east (fig. 17). The upper drainage basin contains the youngest rocks, sandstones and shales of the Atoka[6] , Bloyd and Hale Formations. These rock units make up the Boston Mountains and create the rugged relief characteristic of the upper drainage basin. The Boone Formation, the most extensive formation in the drainage basin, predominantly underlies the middle drainage basin. The Boone Formation is largely made up of chert bearing limestone. Similar to the carbonate formations of the Current River system, it is more easily eroded and susceptible to dissolution – it contains caves and springs and there is less topographic relief in the middle portion of the Buffalo river system. The oldest rocks in the drainage basin are the carbonates and sandstones of the Everton Formation, St. Peter Sandstone, and Powell Formation. These most extensively underlie the lower drainage basin but also occur in the valley bottoms of the upper drainage basin.

Principal components analysis (PCA) was used to identify geologically similar drainage basins in the Buffalo River system (fig. 18). Three main groups are apparent. The first principal component separates two of these groups and corresponds to a shift from sandstone to interbedded sandstone and shale. Richland and Beech cluster together at one end of this axis; the sandstones and shales of the Atoka, Bloyd, and Hale Formations predominate in these drainage basins. Middle, Leatherwood, and Clabber cluster at the other end of this axis, they are all in the lower drainage basin and contain large percentages of the St. Peter sandstone. The second principal component largely coincides with the amount of carbonate (mostly the Boone Formation) in the drainage basins. Most of the middle drainage basins cluster at the upper end of this axis.

## Physiography

Mean drainage area for the study drainage basins was 148 square kilometers (km2) (27,680 acres) with Middle Creek the smallest at 29 km2 (7,057 acres) and the Jacks Fork River the largest at 406 $km^2$ (100,300 acres) (table 7). The mean drainage-basin shape factor was 5.6 and there was no notable difference between the Buffalo and Current River systems. Drainage basins

[6] In order to maintain consistency with our source maps (Hofer and others, 1995; Haley and others, 1993) we refer to the upper-most Pennsylvanian strata in the Buffalo River region as the Atoka Formation. Subsequent geologic mapping suggests that some areas mapped as Atoka Formation may actually be part of the upper Bloyd Formation (for example, Hudson, 1998).

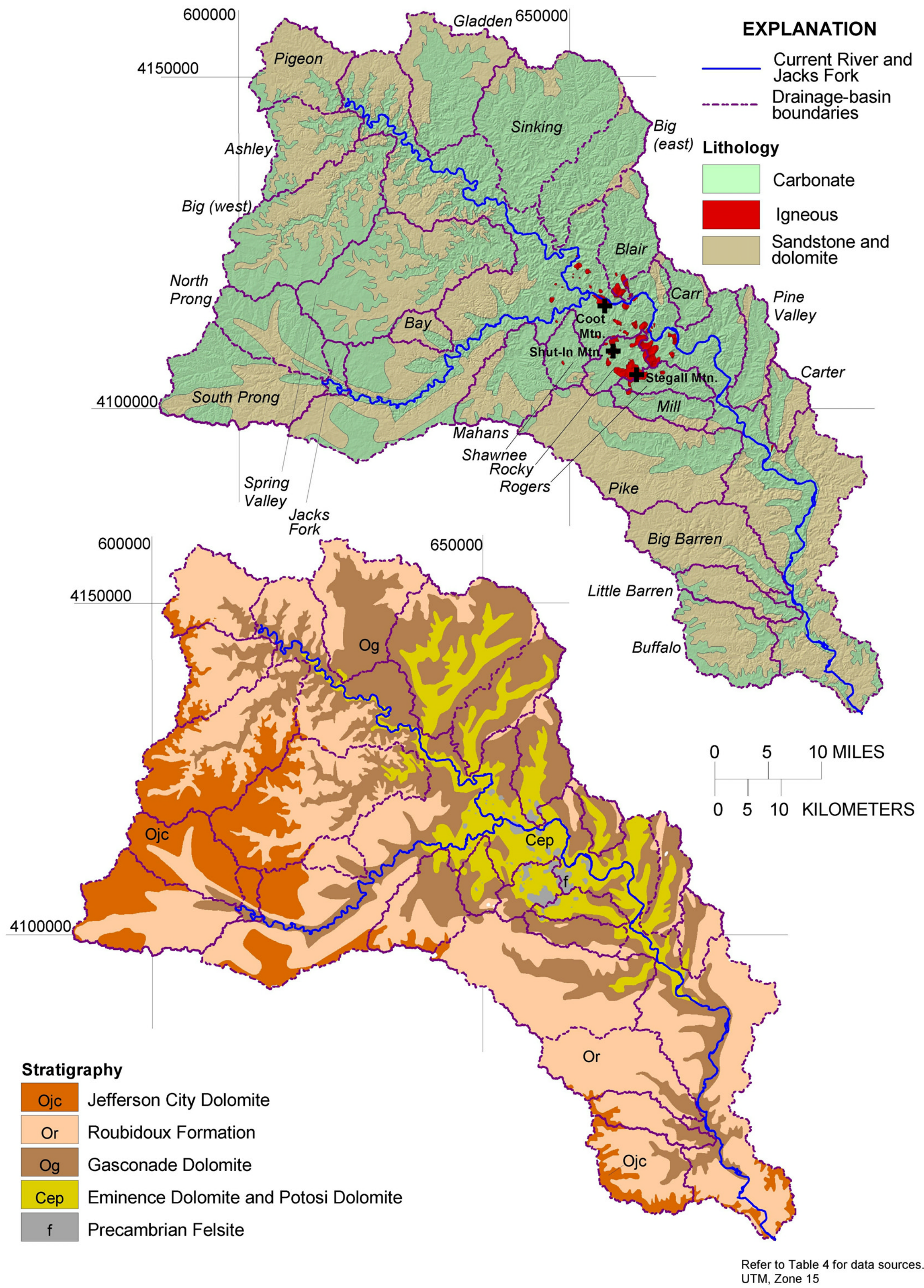



**Figure 15.** Chronostratigraphic and lithologic maps of the Current River drainage basin.

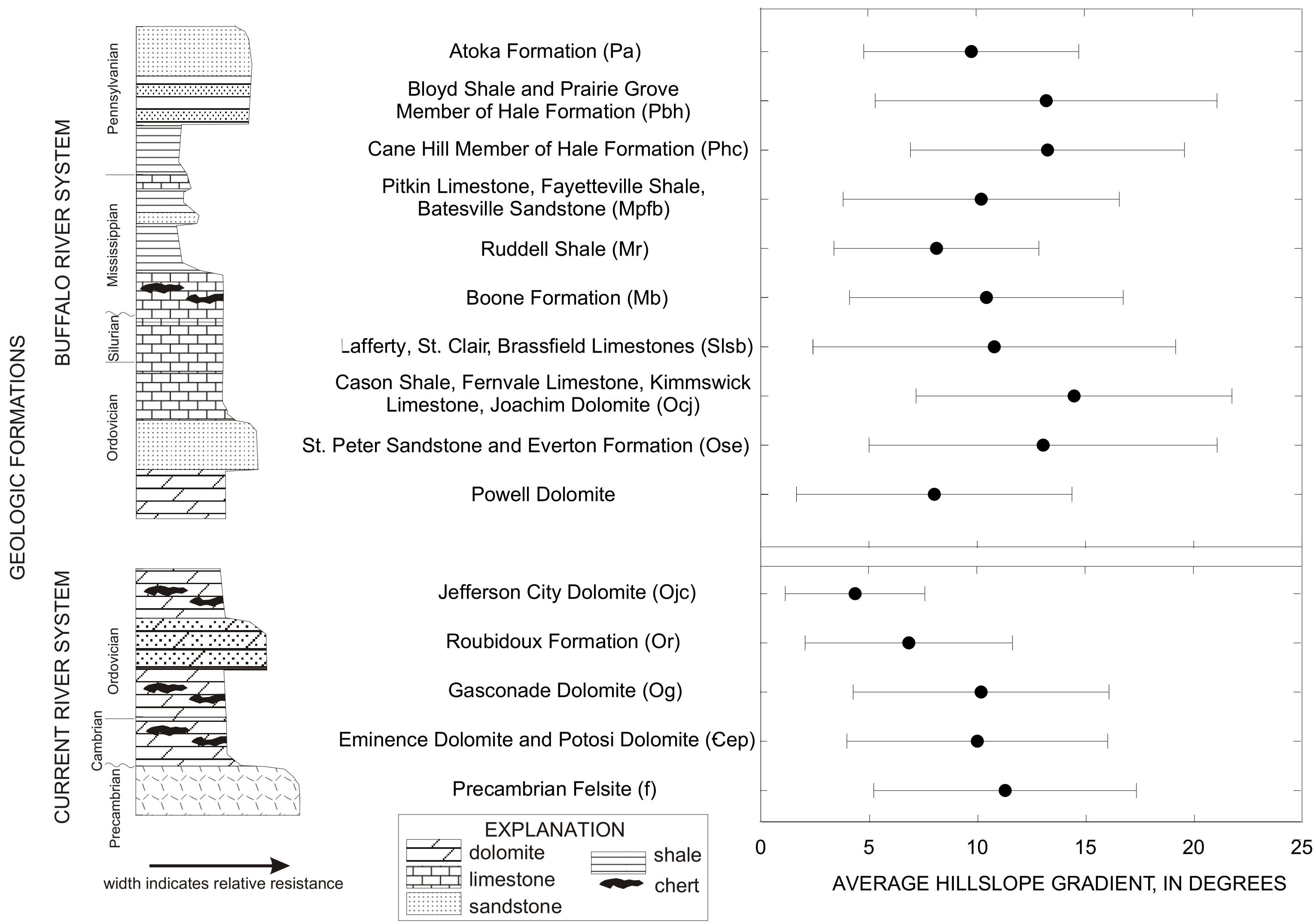



**Figure 16.** Stratigraphic sections for the Current and Buffalo drainage basins (Dean and others, 1979; Haley and others, 1993). The graph to the right shows the average hillslope gradient for areas of the drainage basins mapped with that formation. Gradient was determined for each 30-meter cell in a digital elevation model; bars indicate one standard deviation for the population of cells within each formation.

with unusual shapes include the long and narrow drainage basins of Little Barren, Big (east), and Spring Valley Creeks in the Current and the short and wide drainage basin of Mill Creek (upper) in the Buffalo. Drainage-basin average slopes ranged between 4.9 degrees (Pigeon Creek) and 16.7 degrees (Leatherwood Creek). Pigeon Creek also had the drainage basin with the lowest elevation range, 154 meters, while the Little Buffalo River had the greatest elevation range at 521 meters (table 7; fig. 19A). Five drainage basins in the Current and two in the Buffalo had almost no streamside bluffs while the Little Buffalo River had the maximum with 3.8 percent of its stream buffer classified as bluffs (table 7; fig.19B-C).

### Physiographic Groups

Among our study drainage basins, the three topographic variables are interrelated – drainage basins with high elevation ranges also tend to have steep drainage-basin average slopes (fig. 19A) and many bluffs within the stream buffer (fig. 19B). These differences highlight the distinct physiographic differences between the two river systems. The Buffalo is more rugged than the Current and has drainage basins with steeper slopes, higher elevation ranges and more streamside bluffs (fig. 19A-D).

Topographic characteristics also suggest ways to group drainage basins within the two main river systems. In a scatter plot of elevation range and drainage-basin average slope (fig. 19A), drainage basins cluster according to physiographic and geologic differences. At one extreme are the Buffalo's western and southern drainage basins. Their headwaters are in the Boston Mountains and they have high elevation ranges and physiographic relief. In contrast, the Buffalo's middle and eastern drainage basins have lower elevation ranges and cluster with the study drainage basins of the Current. The middle and eastern drainage basins all fall within the Salem and Springfield Plateaus and their lower elevation ranges reflect the more subtle topography of these regions. Average slopes in the Buffalo tend to be more consistent throughout the drainage basin with the exception of Middle and Leatherwood Creeks, which plot as outliers (fig. 19A). These two drainage basins lack any flat lying uplands and contain extensive bluffs – characteristics that produce an extremely high drainage-basin average slope.

Drainage basins of the Current have fairly consistent elevation ranges but break into two groups according to average slope (fig. 19A). Western drainage basins contain large areas of gently sloping uplands underlain by the Jefferson City Dolomite and the Roubidoux Formation. These low-gradient uplands lower the overall drainage-basin average slope for these tributaries. In contrast, average slopes tend to be higher in the middle and eastern tributaries where the Roubidoux Formation holds up narrow ridges.

### Land Use

While agricultural uses within the parks' drainage basins appear to be increasing (Scott and Hofer, 1995), the overall proportion of cleared land in the early 1990's was less than the proportion of forested land. The maximum proportion of cleared land area in any study drainage basin was 35 percent[7] (table 3) and the mean was 15 percent (table 7). This means that the comparisons within this study are among drainage basins with relatively subtle differences in land use. The study does not provide the perspective of comparisons with intensively agricultural drainage basins.

Within the Buffalo and Current river systems, cleared land tends to be concentrated on flat uplands and in stream valleys (figs. 20-21). The mean proportion of steep, cleared land area was 4 percent with most basins in the Current River system having less than 2 percent steep, cleared land area (table 7). When measured as a proportion of stream buffer area, there was a slightly higher mean proportion of cleared land area, 19 percent. Road densities were slightly higher on average when measured as a proportion of stream buffer area than when measured as a proportion of drainage area. Mean road density in stream buffers was 0.00108 $m/m^2$ and 0.00097 $m/m^2$ in whole drainage basins.

We used principal components analysis to summarize the intensity of human use as measured by the five land-use variables and make comparisons between tributary drainage basins (fig. 22A, B). The first three principal components explain 89 percent of the variation among drainage basins and help identify relations among them. Principal Component 1 (PC 1) appears to be a measure of overall land use intensity with most variables loading equally on this axis. Brush Creek has the most intensive land use (fig. 23A, B) and plots with the highest site score on PC 1. Other drainage basins with relatively high land use intensity include: Big (lower), Calf, Bear, and Tomahawk Creeks in the Buffalo, and Gladden, and Shawnee Creeks in the Current. The drainage basins with the least intensive use are the three smallest drainage basins in the Buffalo River system: Beech, Leatherwood, and Middle Creeks. Leatherwood and Middle Creek drainage basins are insulated from many

[7] Note that these percentages are based in the National Land Cover Data (USGS, 2000) and in some cases differ from other satellite-derived land cover estimates. Refer to Appendix 1 for details.

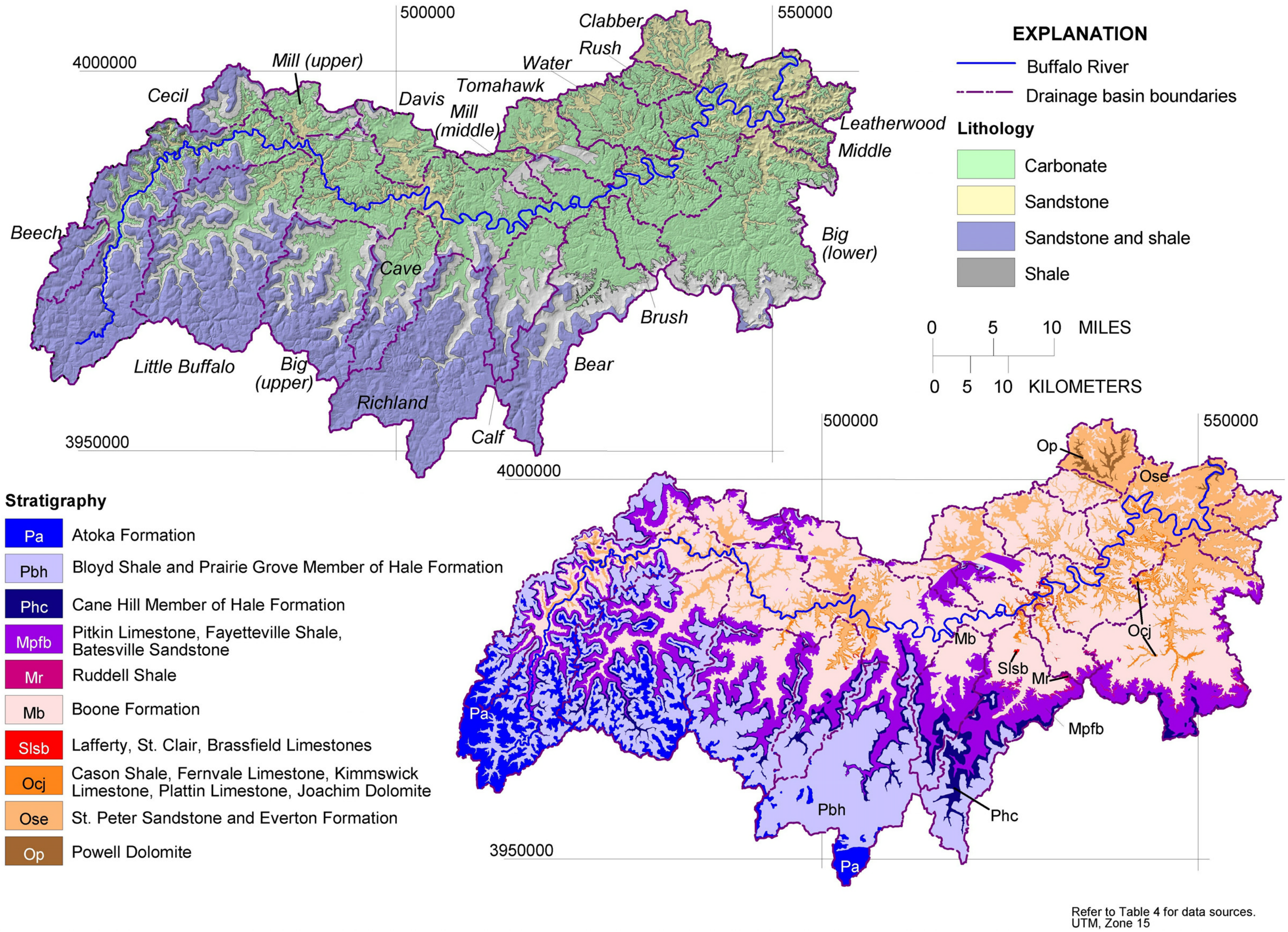



**Figure 17.** Chronostratigraphic and lithologic maps of the Buffalo River drainage basin.

anthropogenic impacts because they are part of the Lower Buffalo Wilderness Area.

Principal Component 2 (PC 2) separates the drainage basins according to the type of land use within them (fig. 22A). It separates drainage basins with a high proportion of cleared land and a low road density (negative values) from those with a low proportion of cleared land and a high road density (positive values). In general, drainage basins in the Current tend to plot near the middle or on the positive end of this axis and have high road densities but a low proportion of cleared land area. Drainage basins with the highest values for PC 2 include Carr, Shawnee, Blair, Mill, Mahans and Pike Creeks. Plots of road density against buffer road density, show that these drainage basins have some of the highest road densities in the study (fig. 23C). In the Buffalo, most drainage basins plot with negative values on PC 2 indicating a relatively high proportion of cleared land but lower road densities. This is in part due to the higher percentage of cleared land mapped on steep slopes in the Buffalo (fig. 23A). Exceptions include Mill (upper), Rush, and Brush Creeks, which also have high road densities.

Principal Component 3 (PC3) further separates the drainage basins according to whether they have a high relative proportion of steep, cleared land area (positive values) or cleared land within stream buffers (negative values) (fig. 22B). In general, there tends to be more cleared land in stream buffers in the Current and more steep, cleared land in the Buffalo. This observation is confirmed in a bivariate scatter plot of cleared land area in buffers vs. steep, cleared land area (fig. 23D). Very few drainage basins in the Current have agriculture on steep slopes, whereas, it is fairly common in the Buffalo, particularly among drainage basins in the Springfield and Salem Plateaus (fig. 23A).

## Relations among Drainage-basin Characteristics

This section describes results from a sequence of correlation and multiple regression analyses we carried out to understand the relations among drainage-basin variables. This analysis is important because sediment and water yield integrate the influence of geologic, physiographic, and land-use factors.

### Correlation Analysis

Table 8 shows correlation matrices for study drainage basins grouped together and separated according to major river system. The analysis for the combined set of drainage basins suggests the following tendencies:

- Variables within a category tend to be related; for example, drainage basins with high average slopes also have high elevation ranges and high proportions of streamside bluffs. Land-use variables also tend to be related; drainage basins with more agriculture overall tend to have high road densities and a greater proportion of cleared land in buffers and on steep slopes.
- Geology to Land Use: There is little relation between geology and land-use variables except for measurements of road density.
- Physiography to Land Use: There is some relation between relief and land-use variables. Drainage basins with lower slopes tend to have a greater proportion of cleared land.

One of the surprises of this correlation matrix is that there is so little relation between geology (as measured as carbonate bedrock area) and physiography. As described previously, scatter plots of relief variables show that drainage basins cluster into physiographically-based groups which appear related to geology (fig. 19A). The correlation analyses for the separate river systems help resolve this disparity – relations between carbonate and relief variables follow opposite trends in the two river systems. In the Buffalo, drainage basins with little carbonate tend to have steeper slopes and greater relief while in the Current, drainage basins with predominately carbonate bedrock have steep slopes. These opposite trends are masked when the two data sets are combined. Another factor may be that because of differences in lithologic descriptions for units in Missouri and Arkansas, geologic characterization was limited to the common lithologic category carbonate.

The separate river-system correlation analyses also suggest some other important relations (table 8). In the Buffalo, there is a positive relation between carbonate and many of the land-use variables. Drainage basins with more carbonate bedrock, the drainage basins in the Salem and Springfield Plateaus, tend to have more intensive land use. Relations between geology and land use are not as strong in the Current, although there is some suggestion of an opposite trend with land-use intensity decreasing as carbonate increases.

### Multiple Regression

The second step in our drainage-basin analyses was to use multiple regression to further test the relations

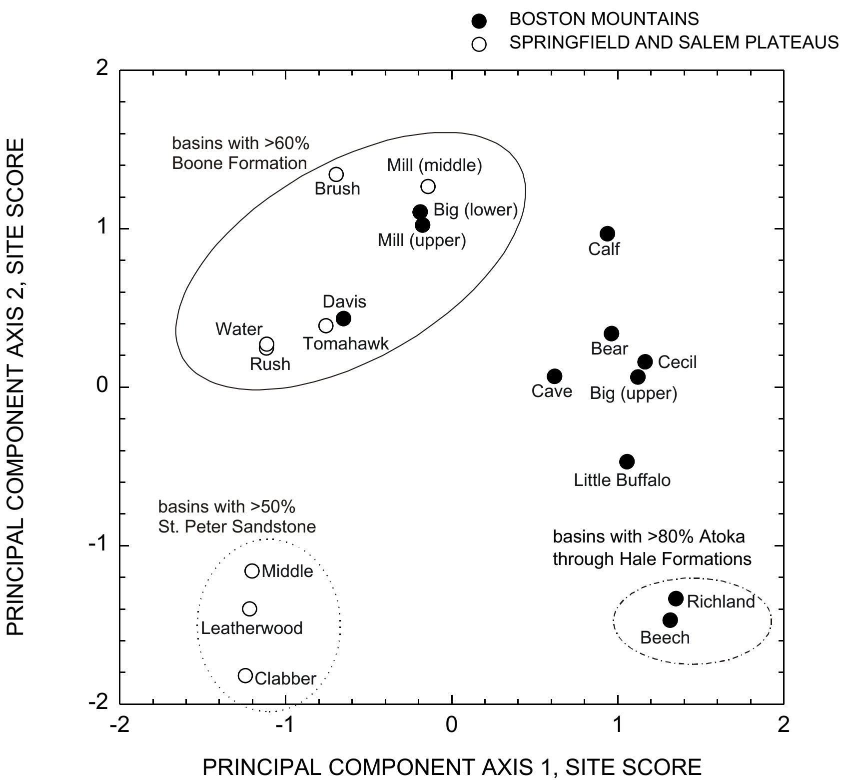



**Figure 18.** Principal components ordination diagram for bedrock lithology in the Buffalo River tributary drainage basins.

identified with Spearman's correlations. The advantage of multiple regression was that it allowed the influence of one variable to be measured after accounting for the impact of another.

## Geologic Influences on Physiography

Multiple regression confirmed the opposite trends between carbonate and relief variables in the two river systems (table 8;fig. 24A, B) and suggested that stratigraphic sequence and regional geologic history may explain the difference. The proportion of carbonate bedrock explained 64 percent of the variation in the drainage-basin average slopes in a regression model with an indicator variable to specify Buffalo or Current and an interaction term to account for the opposite trends in the two river systems (table 9). Measurements of the average slope within each geologic formation help explain this difference (fig. 16). Formations with similar lithologies do not always underly topography with similar gradients. For example, the average slope for terrain underlain by the Gasconade Dolomite is much higher than that underlain by the Jefferson City Dolomite (fig. 16). In the Current, the Gasconade Dolomite is largely exposed in the downcut hillsides of the middle and eastern study drainage basins. As the area of Gasconade Dolomite increases in these drainage basins, so does drainage-basin average slope. In fact, there is little relation between carbonate bedrock area and slope for the western drainage basins of the Current (fig. 24B). In these drainage basins most carbonate bedrock is the younger, sequence-capping Jefferson City Dolomite that underlies gently sloping uplands (fig. 15). This suggests that while there is a relation between lithology and slope it is regional in nature and cannot always be extrapolated between geologic formations. Stratigraphic sequence and geologic history help determine the topographic expression of a particular rock type.

For other physiographic characteristics, stratigraphic differences are also important. For example, one would expect a relation between drainage area and elevation range; larger drainage basins should have a greater elevation drop from the drainage divide to the drainage basin mouth. But a scatter plot of area against elevation range (fig. 19D) show that this is only true for the Current's western drainage basins, for all others, geologic differences have an overriding impact on elevation range (fig. 24B). Drainage basins with Boston Mountain's formations (Atoka, Bloyd, and Hale Formations) have elevation ranges that are almost twice that found in most other study drainage basins (fig. 19D). In the Current, drainage basins with igneous rocks (Rocky, Rogers, Mill Creeks) have some of the greatest elevation ranges in the river system despite their small drainage areas (fig. 19D).

## Geologic and Physiographic Influences on Land-Use Patterns

We also used multiple regression to investigate relations between drainage-basin physiography, geology, and land-use variables. The strongest association is between cleared land area and drainage-basin average slope (fig. 24C, table 9). A regression model with an

**Table 7.** Summary statistics for drainage-basin variables

[$km^2$, square kilometers; m, meters; $m/m^2$, meters per square meter; refer to Table 5 for variable definitions]

| Variable | Mean | Standard deviation | Median | Minimum | Maximum |
|---|---|---|---|---|---|
| **Both River Systems, n = 43** | | | | | |
| Carbonate bedrock area (percent) | 52 | 27 | 57 | 3 (Beech) | 94 (Rogers) |
| Drainage area ($km^2$) | 148 | 115 | 112 | 29 (Middle) | 406 (Jacks Fork) |
| Drainage basin shape factor | 5.6 | 2.2 | 5.0 | 1.5 (Mill (upper) | 11.4 (Little Barren) |
| Elevation range (m) | 277 | 112 | 240 | 154 (Pigeon) | 521 (Little Buffalo) |
| Drainage basin average slope (degrees) | 9.2 | 2.7 | 9.5 | 4.9 (Pigeon) | 16.7 (Middle) |
| Bluff area in stream buffer (percent) | 0.7 | 0.9 | 0.4 | 0.0 (many) | 3.8 (Little Buffalo) |
| Cleared land area (percent) | 15 | 11 | 13 | 0 (Middle, Leatherwood) | 35 (Gladden) |
| Steep, cleared land area (percent) | 4 | 4 | 2 | 0 (Middle, Leatherwood) | 17 (Brush) |
| Cleared land area in stream buffer (percent) | 19 | 12 | 20 | 0 (Beech, Middle, Leatherwood) | 43 (Shawnee) |
| Road density ($m/m^2$) | 0.00097 | 0.00020 | 0.00095 | 0.00035 (Beech) | 0.00145 (Brush) |
| Road density in stream buffer ($m/m^2$) | 0.00108 | 0.00058 | 0.00098 | 0 (Beech) | 0.00248 (Rush) |
| **Buffalo River System, n = 19** | | | | | |
| Carbonate bedrock area (percent) | 44 | 26 | 37 | 3 (Beech) | 89 (Brush) |
| Drainage area ($km^2$) | 128 | 113 | 72 | 29 (Middle) | 369 (Little Buffalo) |
| Drainage basin shape factor | 4.8 | 1.7 | 4.7 | 1.5 (Mill (upper) | 8.6 (Bear) |
| Elevation range (m) | 374 | 103 | 406 | 221 Mill (upper) | 521 (Little Buffalo) |
| Drainage basin average slope (degrees) | 11.1 | 2.4 | 10.9 | 7.6 Mill (upper) | 16.7 (Middle) |
| Bluff area in stream buffer (percent) | 1.2 | 1.1 | 0.9 | 0.0 (Mill (middle) | 3.8 (Little Buffalo) |
| Cleared land area (percent) | 17 | 11 | 16 | 0 (Middle, Leatherwood) | 33 (Tomahawk) |
| Steep, cleared land area (percent) | 6 | 5 | 6 | 0 (Middle, Leatherwood) | 17 (Brush) |
| Cleared land area in stream buffer (percent) | 16 | 12 | 16 | 0 (Beech, Middle, Leatherwood) | 36 (Calf) |
| Road density ($m/m^2$) | 0.00094 | 0.00026 | 0.00094 | 0.00035 (Beech) | 0.00145 (Brush) |
| Road density in stream buffer ($m/m^2$) | 0.00097 | 0.00061 | 0.00084 | 0 (Beech) | 0.00245 (Rush) |

**Table 7.** Summary statistics for drainage-basin variables--Continued

| Variable | Mean | Standard deviation | Median | Minimum | Maximum |
|---|---|---|---|---|---|
| **Current River System, n = 24** | | | | | |
| Carbonate bedrock area (percent) | 59 | 27 | 57 | 10 (Big Barren) | 94 (Rogers) |
| Drainage area ($km^2$) | 164 | 117 | 140 | 40 (Bay) | 406 (Jacks Fork) |
| Drainage basin shape factor | 6.2 | 2.4 | 5.7 | 3.0 (Buffalo) | 11.4 (Little Barren) |
| Elevation range (m) | 201 | 32 | 194 | 154 (Pigeon) | 257 (Rogers) |
| Drainage basin average slope (degrees) | 7.7 | 1.9 | 7.4 | 4.9 (Pigeon) | 11.5 (Big East) |
| Bluff area in stream buffer (percent) | 0.3 | 0.4 | 0.2 | 0.0 (many) | 1.2 (Big East) |
| Cleared land area (percent) | 14 | 11 | 9 | 1 (Blair, Rogers) | 35 (Gladden) |
| Steep, cleared land area (percent) | 2 | 2 | 1 | 0 (Blair, Rogers) | 7 (South Prong) |
| Cleared land area in stream buffer (percent) | 22 | 12 | 24 | 1 (Blair, Rogers) | 43 (Shawnee) |
| Road density ($m/m^2$) | 0.00100 | 0.00013 | 0.00103 | 0.00079 (Buffalo) | 0.00122 (Ashley) |
| Road density in stream buffer ($m/m^2$) | 0.00117 | 0.00055 | 0.00099 | 0.00038 (Bay) | 0.00248 (Carr) |

indicator variable to specify Buffalo or Current, and drainage-basin average slope explained 60 percent of the variation in cleared land area. After introducing another explanatory term, private land area within a drainage basin, the regression model explains 81 percent of the variation (table 9). This supports observations that when land is held privately, slope is often the main determinate in whether it will be cleared and converted to pasture. In the Buffalo River system, land with a slope less than 15 degrees is more likely to be cleared (D. Mott, Hydrologist, Buffalo National River, oral communication, 2000). It is also interesting that the relation between slope and cleared land area is weakest in basins with the lowest average slopes (fig. 24D). This supports the hypothesis that in basins with gentler topography, slope no longer exerts a strong influence on land-use patterns.

The regression model also illustrates an important difference between cleared land in the Buffalo and Current river systems (table 9; fig. 24C). For a given average slope, the regression model indicates that drainage basins in the Buffalo have 1.3 times as much cleared land as those in the Current. This may reflect differences in the availability of low gradient land in the two regions – in the more rugged Buffalo, farmers are more likely to raise cattle on steeper slopes. Scatter plots of cleared land and steep, cleared land show that drainage basins in the Buffalo have more cleared land on steep slopes (fig. 23A). This observation suggests that while the proportion of agriculture affecting the two parks is similar, agriculture is likely to have a greater impact in the Buffalo River system. Agriculture and the potential for accelerated erosion, is occurring in landscape positions where steep slopes increase the potential for high transport capacity (table 1).

We also used multiple regression to investigate whether there is a relation between geology and land use patterns after accounting for differences in slope and private land area. There is often a strong relation between these two variables in regions dominated by row crop agriculture – geology influences many soil characteristics that determine agricultural potential. A significant regression model for study drainage basins in the Current indicates an increase in cleared land area is associated with an increase in carbonate bedrock and private land area and a decrease in basin average slope (table 9).

This case is a good example of the different information provided by correlation analysis and multiple regression. In the Current, a bivariate relation between carbonate bedrock and cleared land is not apparent (fig. 25A). But when multiple regression is used to adjust for differences in basin average slope and private land area, a relation between carbonate bedrock and cleared

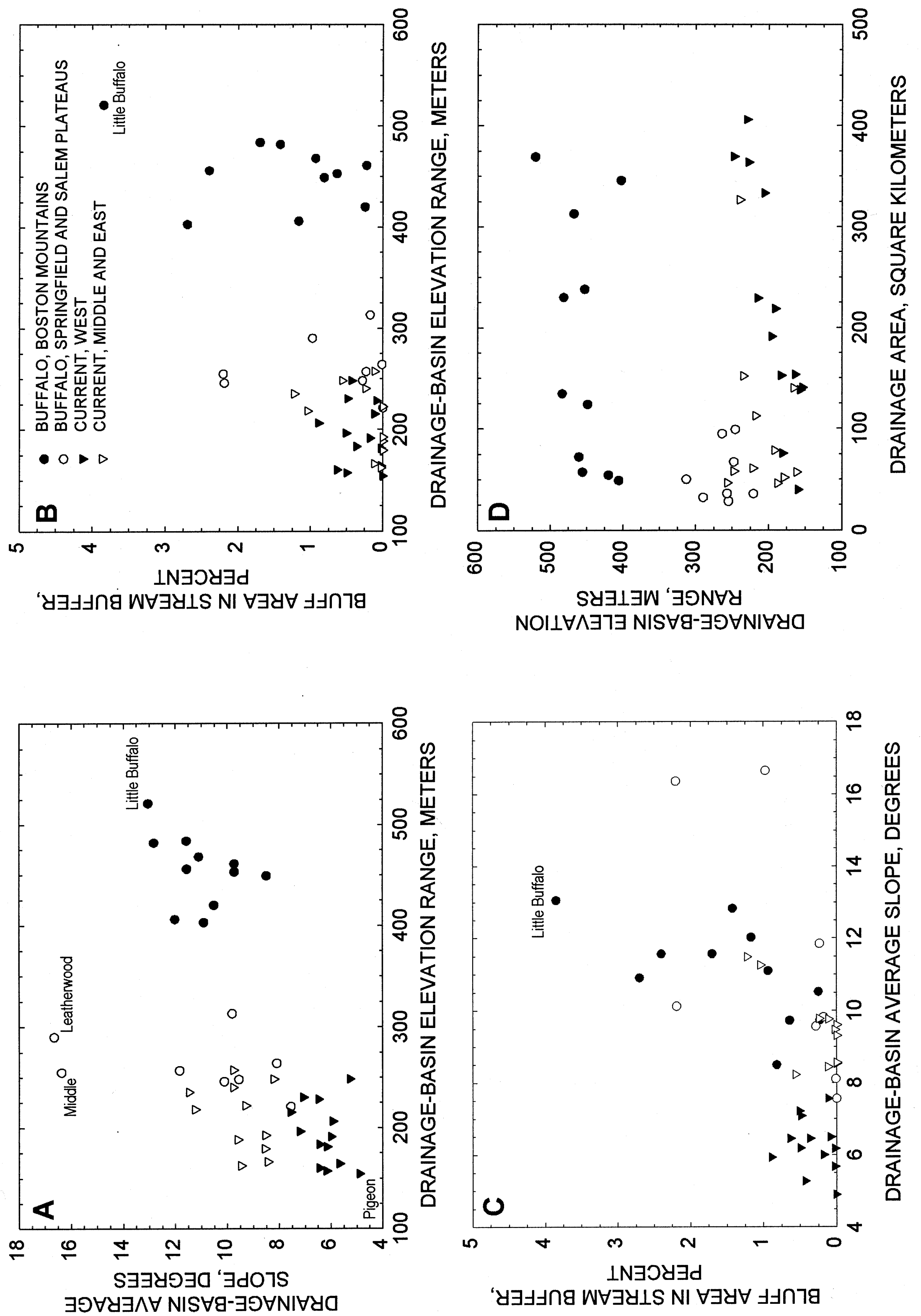



**Figure 19.** Scatter plots of drainage-basin relief variables.

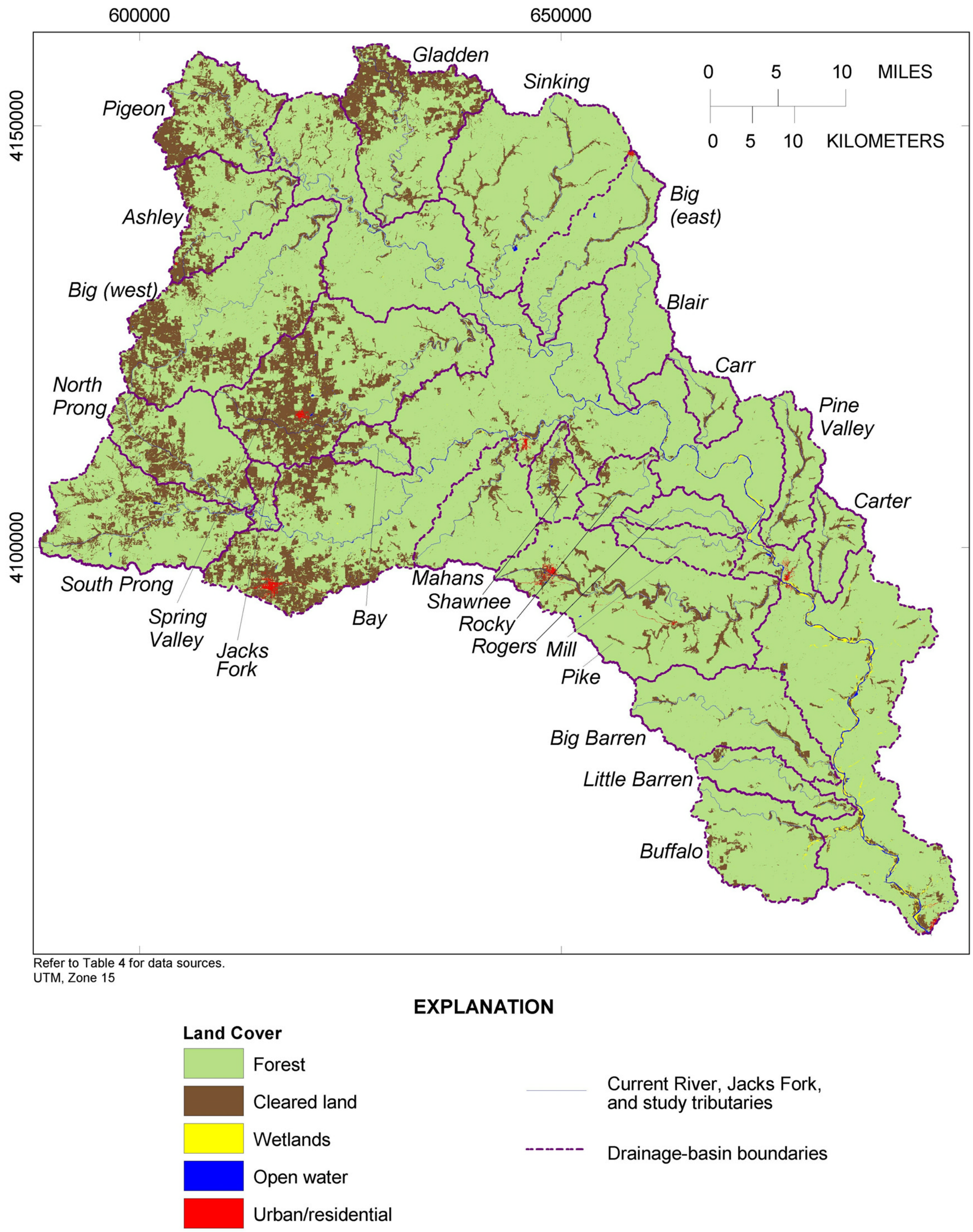



**Figure 20.** Map of land cover distributions within the Current River drainage basin.

land area becomes significant (table 9). This relation can be seen graphically by plotting the partial residual from the regression model (fig. 25B). The partial residual adjusts the response variable by accounting for variation explained by other explanatory variables in the model. This model shows that there is an association between carbonate bedrock and cleared land in the Current, but the association is masked by differences in basin average slope and private land area. In the Buffalo, the opposite case is true: a scatter plot (fig. 25C) and Spearman's correlations show a bivariate relation between carbonate bedrock and cleared land, but a regression model that also accounted for differences in basin average slope and private land area was not significant.

We also assessed relations between physiography and land use patterns by looking for differences between the four physiographic groups of the parks. Scatter plots highlight differences between drainage basins in the middle and eastern Current and the western Current (fig. 23). Middle and east drainage basins tend to have low overall percentages of cleared land area but the cleared land that exists is concentrated in stream valleys (fig. 23B). Middle and east drainage basins have similar road densities to the west drainage basins of the Current, but again, more roads are concentrated in stream valleys in the middle and east drainage basins (fig. 23C). These trends likely result from the more rugged topography of the eastern drainage basin. Steeper slopes are less suitable for pasture or roads and so they are concentrated in stream valleys. In contrast, in the west drainage basins of the Current, roads and cleared land are more evenly distributed between valley bottoms and flat lying uplands (fig. 23B, 23C). As the overall percentage of cleared land area in these drainage basins increases, so does the proportion of cleared land in stream buffers and the overall road density.

There are fewer differences in land use patterns between the physiographic groups of the Buffalo River system. A subtle distinction is that Boston Mountain's drainage basins tend to have more agriculture in stream buffers and less cleared land on steep slopes than the Springfield/Salem Plateau drainage basins (fig. 23D). This may in part relate to the distribution of the Boone Formation, the most common rock type underlying agricultural lands in the Buffalo. It commonly is found in valley bottoms in the Boston Mountain's drainage basins, and where it occurs, these valleys tend to be wider and more suitable for agriculture than valleys underlain by other rock types. An example of this occurs along the Buffalo River main stem near its confluence with Richland Creek (fig. 17). Upstream of the confluence, the Buffalo flows through the St. Peter Sandstone and the valley is narrow. Downstream of the confluence, the river flows through the Boone Formation and the valley suddenly becomes broader. This phenomenon likely relates to the lower erosional resistance of the Boone Formation.

In summary, within basin-scale analyses suggest a relation between land-use patterns and physiography and highlight the regional nature of relations between geology and physiography. In both the Buffalo and the Current, cleared land is more likely to occur on shallower slopes and on carbonate bedrock. However, the two drainage basins differ in their relations between slope and geology. In the Buffalo, shallower slopes are more likely to occur in drainage basins with more carbonate bedrock, while in the Current, they are more likely to occur in drainage basins with less carbonate bedrock. These opposite trends relate to the different stratigraphic position and weathering history of the carbonate rock formations in each drainage basin. Physiography is related to geology but in a way that reflects geologic history and stratigraphic sequence. This is a reminder that even within the Ozarks, associations between geology and physiography are not always consistent between regions.

# Results: Tributary Reach Characteristics

This section presents data from the reach-scale habitat inventories. It includes summary data from measurements of reach geometry, substrate, and reach stability and discusses relations between reach scale and basin-scale data sets. The between-scale comparisons evaluate whether data from the Buffalo and Current River tributaries support the many hypothesized links between drainage-basin characteristics and streams conditions (table 1).

## Channel Geometry

Gradients in the study tributary reaches range between 0.0106 and 0.0009 (table 3; table 10). The tributaries typically have meandering channels with alternating gravel bars and a sequence of thalweg habitats progressing from a riffle (typically at a bar head), to a race, to a pool, to a glide, and back again to a riffle. This progression is apparent in an example longitudinal profile from Sinking Creek where each survey point is labeled with the habitat designation given during surveying (fig. 26A). Riffles form the shallowest sections of the longitudinal profile and tend to have steep, downward-sloping bed topography and the highest water surface gradients (fig. 6). Races tend to occur at the base of the riffles where flow deepens and converges but

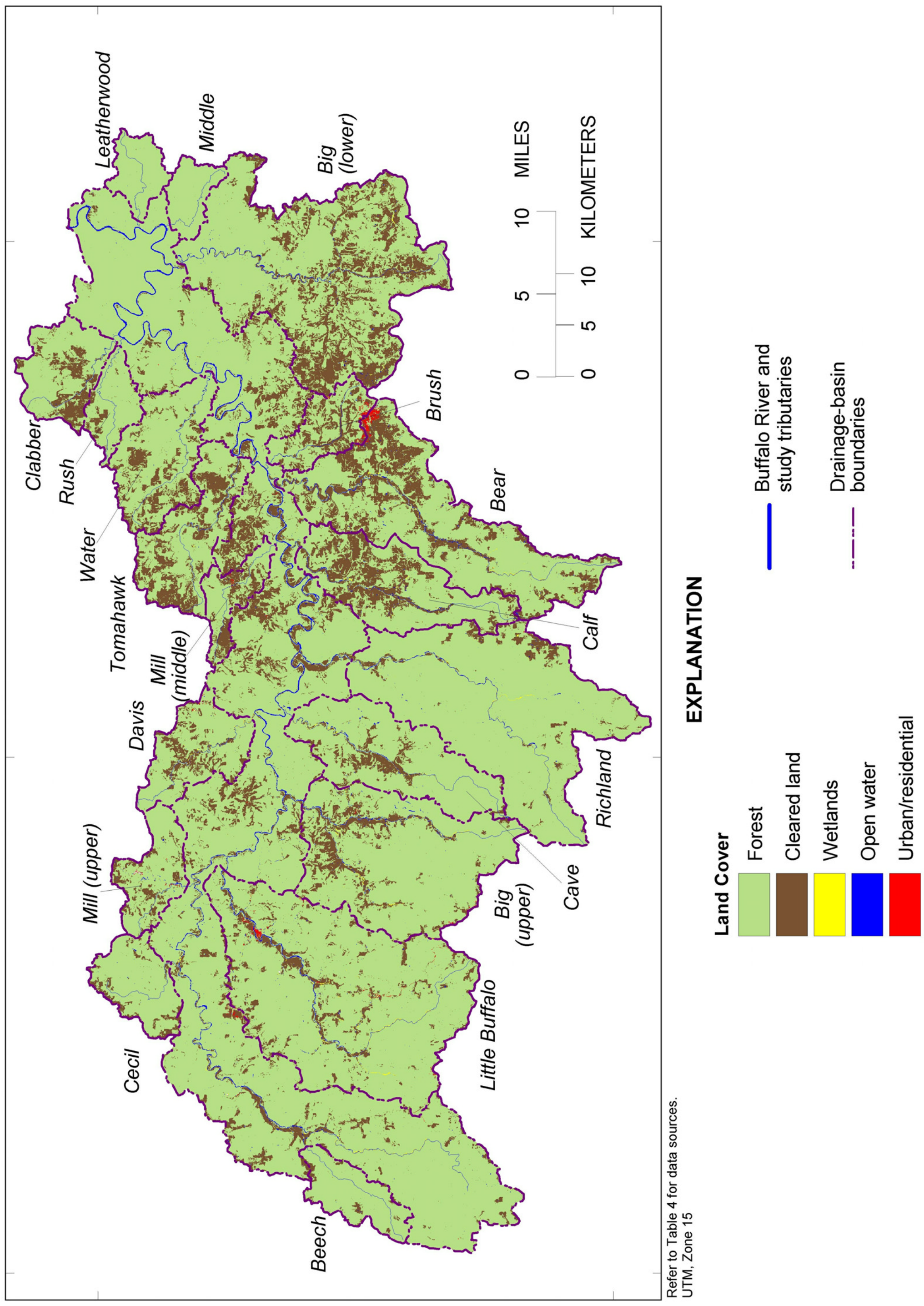



**Figure 21.** Map of land cover distribution within the Buffalo River drainage basin.

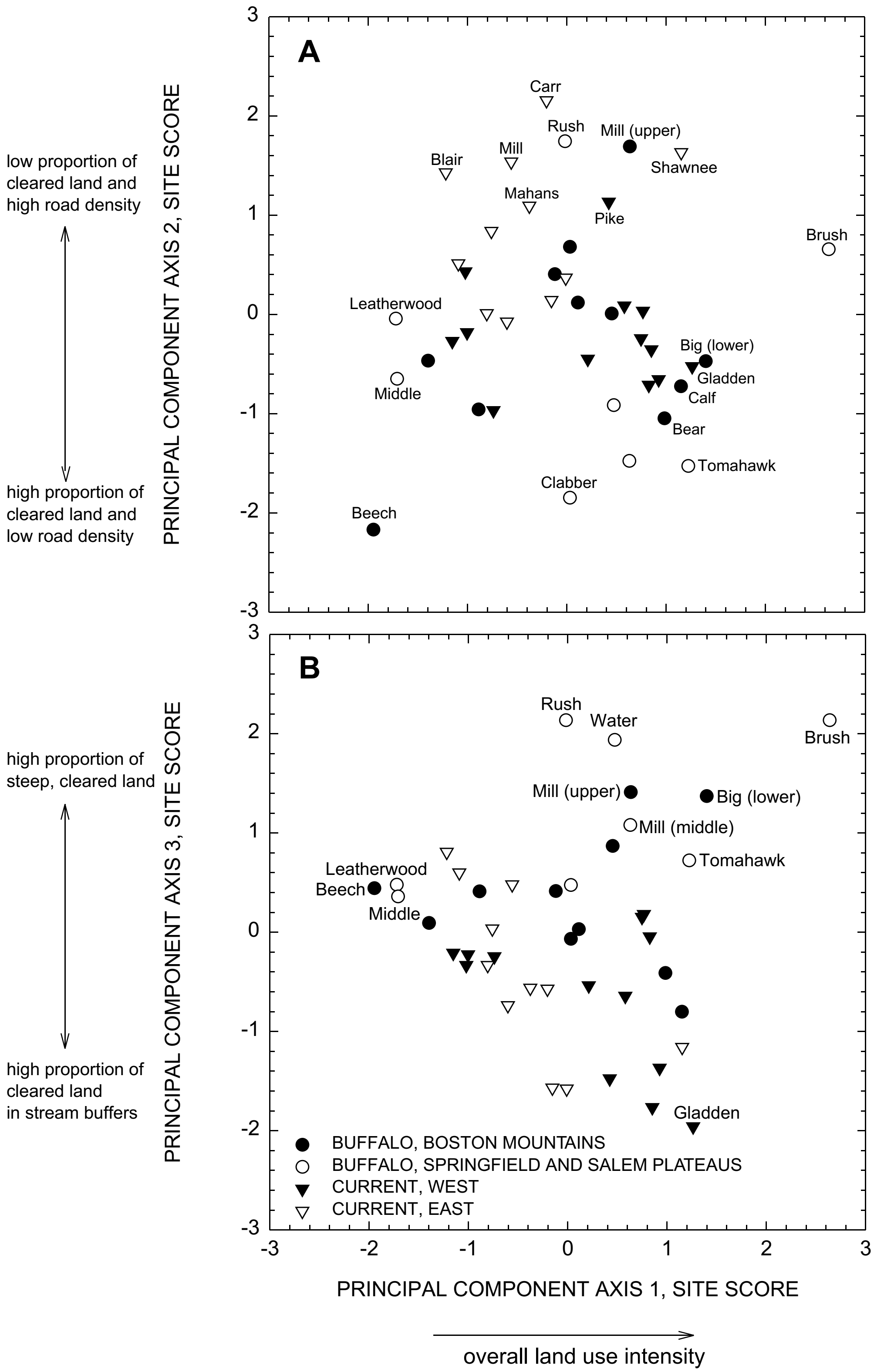



**Figure 22.** Principal components ordination diagrams for land-use variables.

velocities remained high. Pools usually followed races – the long profile for Sinking Creek shows the greater depths and nearly flat water-surface gradient that was typical of these habitats. Glide habitats are often found at the ends of pools where the bed topography slopes upward toward the riffle crest and creates shallower depths (fig. 26A). For the 36 study reaches, glides and pools were the most common habitat types with each making up about one third of a study reach on average (table 10).

Four of the smaller drainage basins have streams with gradients over 0.0080 (table 3) and channel morphologies that differed from the typical pool-riffle sequence. In the Buffalo River system these were Middle (fig. 26B), Clabber, and Leatherwood Creeks, and in the Current River system, Bay Creek. The three Buffalo channels have a large proportion of bedrock, with Clabber Creek including a small, bedrock waterfall and Middle and Beech Creeks containing sections of bedrock bottomed, step-pool channel morphology (fig. 10B). In the Current, Bay Creek has both a long, deep, bluff pool and a steep step-pool section.

Channel geometry data show that streams with lower gradients have larger bankfull channel dimension (table 11). Average glide bankfull channel widths and depths ranged between 12.4-37.5 m and 0.47-1.5 m respectively (table 10). Streams with large cross-sectional channel geometries also have long, deep residual pools (table 11). Average residual pool lengths and depths range between 21.4-258.1 m and 0.15-0.95 m for the study sites (table 10).

## Relations between Channel Geometry and Drainage-basin Characteristics

### Correlation Analysis

Relations between channel geometry and drainage-basin characteristics were explored with scatter plots and Spearman's correlations (table 12; fig. 27). Table 12 shows correlation matrices for all study drainage basins grouped together and separated by river system, Buffalo or Current. In all matrices, the strongest correlations are between drainage area and the channel geometry measures – large drainage basins have channels with large dimensions and shallow gradients (fig. 27A). Increases in both bankfull and residual pool dimensions are associated with an increase in drainage area (fig. 27B-E). These relations follow long noted hydraulic relations between drainage area, discharge, and channel dimensions (for example, Leopold and Maddock, 1953).

Larger drainage basins also tend to have a greater proportion of low gradient habitats than smaller drainage basins. This is apparent in both the qualitative habitat classification data and in residual pool calculations. The proportion of reach length classified as pool or glide habitats is positively correlated with drainage area (fig. 27F-G), as is the proportion of reach length within residual pools (fig. 27H). This relation illustrates the loss of high-energy habitats in large streams – glide and pool habitats predominate and there is a lower relative abundance of riffles than in smaller streams.

The scatter plots also help illustrate differences between the Buffalo and the Current river systems. Measurements of bankfull geometry show that for drainage basins of comparable size, the Current River tributaries have smaller bankfull channel widths and depths than tributaries of the Buffalo River (fig. 27B-C).

### Multiple Regression

We used multiple regression to investigate relations between channel geometry variables and other basin-scale variables after accounting for relations with drainage area. Table 13 summarizes the series of significant regression models for each channel geometry variable and all study drainage basins. The table illustrates one of the ambiguities of multiple regression – multiple models can explain similar amounts of variation in the data set. Without other lines of evidence or additional studies, it is impossible to identify which model is better, only that there is an equally strong association with two different sets of explanatory variables. Nevertheless, multiple regression helped identify trends by showing associations that are consistent for different measures of channel geometry.

The most common regression model for all of the different channel geometry measures is one that includes drainage area and a drainage-basin relief variable. After accounting for differences in drainage area, drainage-basin relief elements are positively related to bankfull channel dimensions, residual pools, and the proportion of glide habitats (table 13; fig. 28). These relations support the hypothesis that drainage-basin relief elements increase storm flow. Larger channels would accommodate the flashier run-off and greater storm flows generated in steep terrain (table 1). For many of the channel geometry variables, three competing models support this hypothesis. After accounting for differences in drainage area, an increase in channel dimensions is associated with an increase in elevation range, an increase in drainage-basin average slope, or an indicator variable specifying river system, Buffalo or Current (table 13).[8] The three variables appear to act as proxy variables for each other – when one is in the regression model, the other two variables are not significant. The

[8] Bankfull depth has a third competing model: relief measured as the percentage of streamside bluffs.

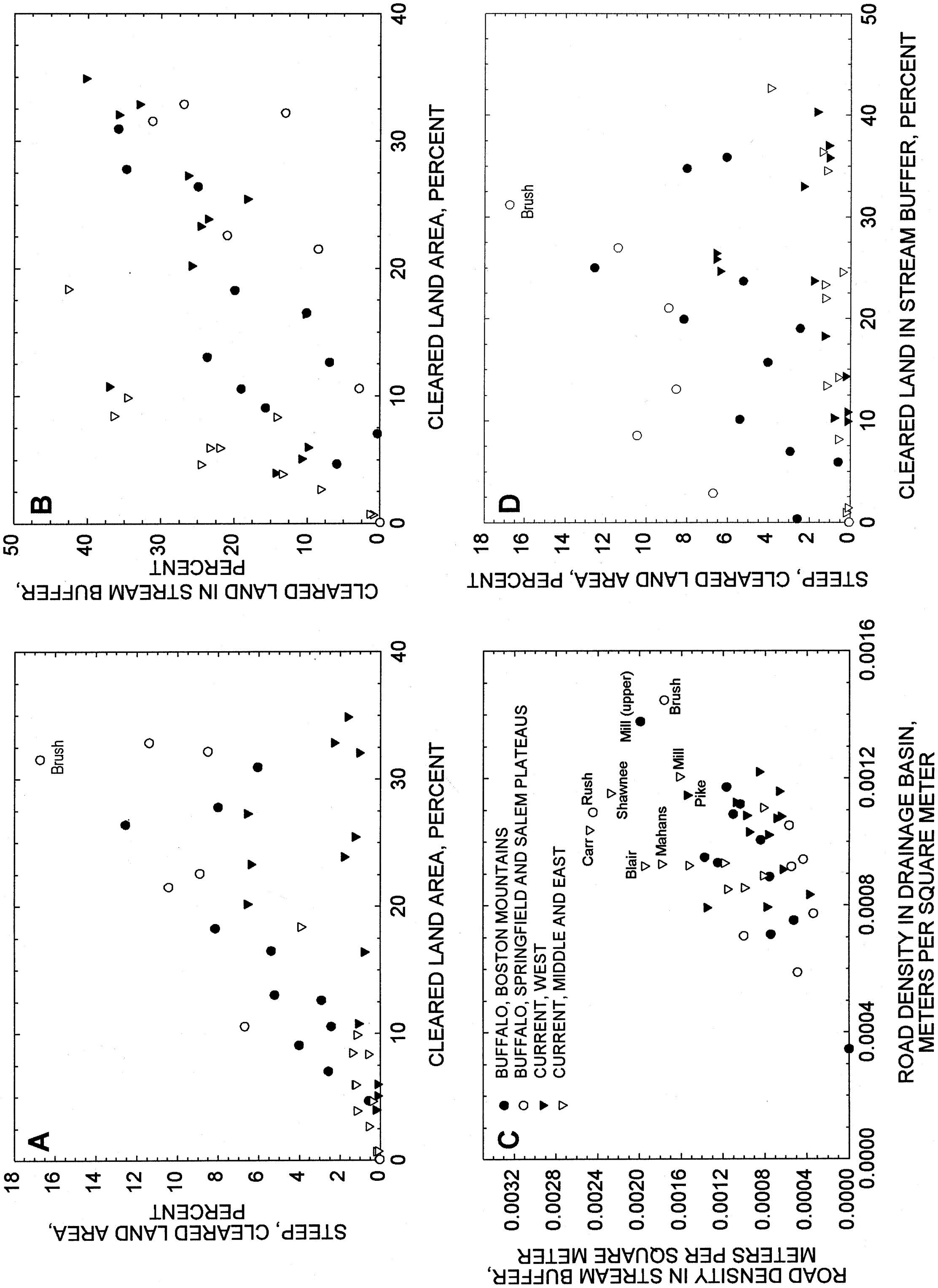



**Figure 23.** Selected scatter plots of land-use variables.

**Table 8.** Spearman rank correlation coefficients for relations between drainage-basin variables

[shaded values significant at p ≤ 0.05; bold values > 0.5 or < -0.5; refer to Table 5 for variable definitions]

| Variable | Carbonate bedrock area | Drainage area | Drainage basin shape | Elevation range | Drainage basin average slope | Bluff area in stream buffer | Cleared land area | Steep, cleared land area | Cleared land in stream buffer | Road density | Road density in stream buffer |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Both River Systems, n = 43** | | | | | | | | | | | |
| Carbonate bedrock area | **1.00** | | | | | | | | | | |
| Drainage area | -0.23 | **1.00** | | | | | | | | | |
| Drainage basin shape | 0.11 | 0.19 | **1.00** | | | | | | | | |
| Elevation range | -0.16 | 0.04 | -0.05 | **1.00** | | | | | | | |
| Drainage basin average slope | 0.04 | -0.30 | -0.21 | **0.71** | **1.00** | | | | | | |
| Bluff area in stream buffer | -0.31 | 0.20 | -0.06 | **0.57** | **0.56** | **1.00** | | | | | |
| Cleared land area | -0.06 | 0.27 | -0.04 | -0.01 | -0.46 | -0.10 | **1.00** | | | | |
| Steep, cleared land area | 0.07 | 0.10 | -0.25 | 0.33 | 0.09 | 0.08 | **0.74** | **1.00** | | | |
| Cleared land area in stream buffer | 0.05 | 0.42 | 0.05 | -0.24 | -0.49 | -0.36 | **0.63** | 0.37 | **1.00** | | |
| Road density | 0.36 | 0.16 | 0.16 | -0.06 | -0.17 | -0.19 | 0.37 | 0.32 | 0.38 | **1.00** | |
| Road density in stream buffer | 0.39 | 0.03 | 0.05 | 0.00 | 0.19 | -0.20 | -0.27 | -0.04 | 0.19 | 0.47 | **1.00** |
| **Buffalo River System, n = 19** | | | | | | | | | | | |
| Carbonate bedrock area | **1.00** | | | | | | | | | | |
| Drainage area | -0.35 | **1.00** | | | | | | | | | |
| Drainage basin shape | 0.12 | 0.24 | **1.00** | | | | | | | | |
| Elevation range | **-0.58** | **0.63** | 0.06 | **1.00** | | | | | | | |
| Drainage basin average slope | -0.37 | -0.11 | -0.33 | 0.30 | **1.00** | | | | | | |
| Bluff area in stream buffer | -0.46 | 0.38 | -0.23 | 0.36 | **0.64** | **1.00** | | | | | |
| Cleared land area | 0.49 | 0.15 | 0.24 | -0.30 | **-0.89** | **-0.53** | **1.00** | | | | |
| Steep, cleared land area | **0.63** | 0.16 | 0.12 | -0.40 | **-0.72** | -0.41 | **0.88** | **1.00** | | | |
| Cleared land area in stream buffer | 0.16 | **0.54** | 0.24 | 0.20 | **-0.65** | -0.25 | **0.80** | **0.65** | **1.00** | | |
| Road density | **0.57** | 0.21 | 0.16 | 0.13 | -0.14 | -0.07 | 0.33 | 0.41 | 0.36 | **1.00** | |
| Road density in stream buffer | 0.34 | 0.21 | 0.02 | 0.40 | 0.12 | -0.16 | 0.03 | 0.16 | 0.25 | **0.73** | **1.00** |

**Table 8.** Spearman rank correlation coefficients for relations between drainage-basin variables--Continued

| Variable | Carbonate bedrock area | Drainage area | Drainage basin shape | Elevation range | Drainage basin average slope | Bluff area in stream buffer | Cleared land area | Steep, cleared land area | Cleared land in stream buffer | Road density | Road density in stream buffer |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Current River System, n = 24** | | | | | | | | | | | |
| Carbonate bedrock area | **1.00** | | | | | | | | | | |
| Drainage area | -0.23 | **1.00** | | | | | | | | | |
| Drainage basin shape | 0.03 | 0.07 | **1.00** | | | | | | | | |
| Elevation range | **0.51** | 0.32 | 0.38 | **1.00** | | | | | | | |
| Drainage basin average slope | **0.71** | -0.42 | 0.00 | 0.39 | **1.00** | | | | | | |
| Bluff area in stream buffer | 0.06 | 0.30 | 0.22 | 0.37 | 0.03 | **1.00** | | | | | |
| Cleared land area | -0.37 | 0.43 | -0.21 | -0.31 | **-0.74** | 0.04 | **1.00** | | | | |
| Steep, cleared land area | -0.04 | 0.35 | -0.41 | -0.25 | -0.20 | 0.05 | **0.72** | **1.00** | | | |
| Cleared land area in stream buffer | -0.14 | 0.29 | -0.14 | -0.20 | -0.27 | -0.30 | **0.70** | **0.68** | **1.00** | | |
| Road density | 0.16 | 0.11 | 0.12 | 0.04 | -0.08 | -0.15 | 0.36 | 0.46 | 0.39 | **1.00** | |
| Road density in stream buffer | 0.38 | -0.19 | 0.01 | 0.19 | **0.65** | -0.15 | -0.48 | -0.08 | 0.10 | 0.13 | **1.00** |

basin-scale analyses help explain these relations. They showed that slope and elevation range are related to each other and that drainage basins in the Buffalo river system tend to have both greater elevation ranges and steeper slopes than drainage basins in the Current river system (fig. 19A). Channel dimensions are associated with these three co-varying variables – slope steepness, elevation range, and the distinction between the two main river systems.

The competing models are a reminder that regression demonstrates associations between variables but not cause and effect. Drainage basins in the Buffalo may have larger channel dimensions because steep slopes or high elevation ranges, or because of some other parameter that also differs between the two main river systems. For example, we know that there is a difference in the prevalence of karst hydrology in the two river systems. The Current, with its more widespread carbonate bedrock has an extensive karst hydrologic network with many springs, caves, and underdrained streams. The smaller channels in the Current may relate to this characteristic – small channels may form in drainage basins where much of the flow is diverted to the underground drainage system (fig. 29). Comparisons of channel width and drainage area show that the five large drainage basins with unusually narrow widths are Spring Valley, Big (west), Gladden, Ashley, and Buffalo Creeks, all west Current drainage basins with underdrained streams (fig. 27B). The regression models help identify related variables and suggest multiple working hypotheses, but it may remain difficult to select one model over another. In this example, the data support two hypotheses – that greater relief creates greater storm flows and larger channels or that channels are smaller in drainage basins where karst networks and subsurface flow reduce storm flows.

Current River system sites also show a weaker relation between average residual pool depth and basin area than those in the Buffalo River system. Large Current tributary drainage basins do not necessarily have deep residual pools. This again may relate to the prevalence of karst – with part of their run-off diverted to sub-surface channels and fractures, storm flows from the karst basins may be less able to scour deep pools.

Several of the channel-geometry variables also show an association with land-use or geology variables. For example, an increase in the proportion of pool habitats within a reach is associated with a decrease in cleared land area within a drainage basin (table 13). This relation supports the hypothesis that anthropogenic-related erosion may generate a higher sediment supply and smoother channels with fewer pools (table 2). However, the relation between slope and cleared land area confounds the strength of this association. We

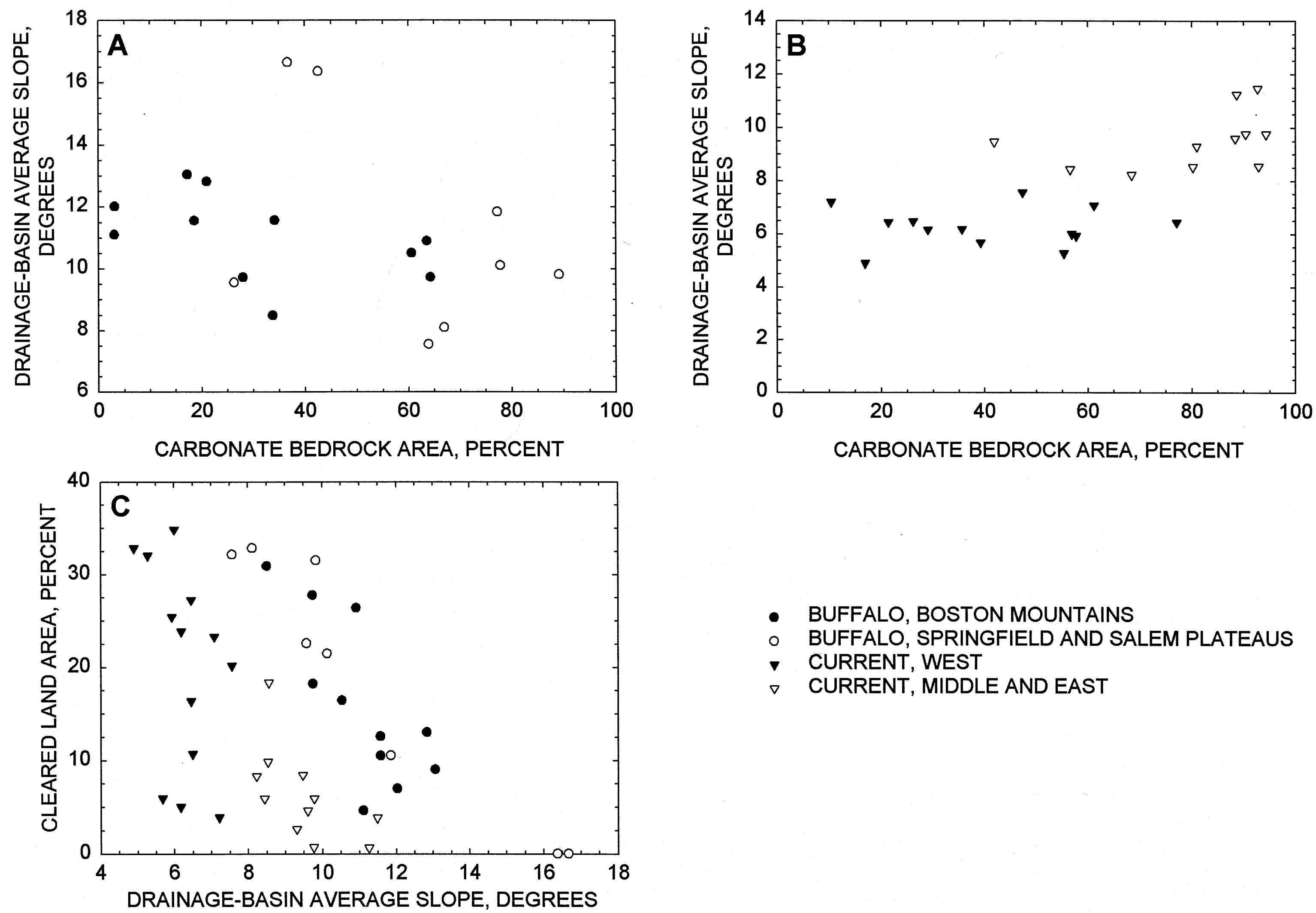



**Figure 24.** Selected scatter plots of related drainage-basin variables. A-B. Scatter plots of carbonate bedrock area and drainage-basin average slope showing opposite trends in the Buffalo and Current River systems. C. Scatter plot of drainage-basin average slope and cleared land area.

**Table 9.** Selected multiple regression models for drainage-basin variables; explanatory variables signficant at $p \leq 0.05$

| Response variable | Sample size | Intercept | Model coefficients for explanatory variables | | | | | R squared |
|---|---|---|---|---|---|---|---|---|
| | | | | Geology | Physiography | Land use | Interaction | |
| | | | Indicator for river system[1] | Carbonate bedrock area, as a proportion | Drainage basin average slope, in degrees | Private land area, as a proportion[2] | Product of carbonate bedrock area and indicator for river system | |
| **Both River Systems** | | | | | | | | |
| Drainage basin average slope, in degrees | 43 | 11.6426 | -6.8334 | -2.5835 | | | 7.5841 | 0.64 |
| Cleared land area, as a proportion | 41 | 0.6652 | -0.1791 | | -0.0449 | | | 0.60[3] |
| | 41 | 0.3073 | -0.1100 | | -0.0336 | 0.1008 | | 0.81[3] |
| **Current River System** | | | | | | | | |
| Cleared land area, as a proportion | 17 | 0.2230 | | 0.1741 | -0.0516 | 0.1067 | | 0.89 |

[1] Indicator variable specifies river system, Buffalo = 0 or Current = 1.

[2] Variable transformed, $e^x$.

[3] Middle, Leatherwood excluded.

know from the basin-scale analyses that cleared land area was negatively associated with drainage-basin average slope. Without drainage-basin average slope in the regression model, it is possible that the proportion of pools is related to drainage-basin average slope and not to cleared land area.

This example is also an illustration of the challenges imposed by related explanatory variables – relations with response variables are most convincing when the model accounts for anticipated relations with other explanatory variables. In this example, associations with land use or geology variables are most convincing when regression models also account for differences in drainage area and relief elements. An example where such a model exists is with bankfull depth. After accounting for differences in drainage area and main river system, bankfull depth is negatively associated with cleared land area (fig. 30). This model supports the hypothesis that by increasing bed load sediment supply, land clearing leads to shallower stream channels. However, two caveats moderate the strength of this conclusion. First, the model does not account for geologic differences between the study drainage basins. Basin-scale analyses showed a correlation between carbonate bedrock and cleared land area among the Buffalo tributary drainage basins (table 8; fig. 25B). It is possible that cleared land area is acting as a proxy variable for geologic differences. Second, inspection of the partial residual plot shows an opposite trend among middle and east Current drainage basins than among the overall data. While the overall trend of the data shows a negative association between cleared land area and bankfull depth, there is a positive association for the middle and east Current group.

The consistent association between relief elements and channel geometry highlight the difference in channel geometry between the two river systems, Buffalo and Current. To investigate river-system specific relations, data were also analyzed in Buffalo and Current River groups. Subsets of the data helped identify more subtle relations by eliminating variation related to relief or river system. It is important to note however, that as drainage basins were subset, sample size decreased and the ability to statistically detect relations diminished.

### Buffalo River System

In the Buffalo, the drainage-basin variables most strongly correlated with channel geometry measures are carbonate bedrock area and the three measures of cleared land area. After accounting for differences in drainage area, average bankfull depth, average residual pool depth, the proportion of residual pools, and the proportion of pool habitats, are all negatively associated with carbonate bedrock or with the three variables measuring cleared land area (table 14). As with the relief variables in the combined drainage basin models, the four variables act as proxy variables for each other, when one is in the model the others are not significant. The variables appear to act as proxies because of their correlations with each other – drainage basins with more carbonate bedrock also have more cleared land (table 8). This is apparent visually in geology and land cover maps (figs. 16 and 21). The carbonate Boone Formation underlies the middle and lower drainage basins of the Buffalo river system where pasture and cleared land are concentrated. The regression models suggest that the tributaries in this part of the river system have shallower pools and bankfull depths and a lower abundance of pool habitats. Because of the relation between explanatory variables, we cannot determine whether these characteristics are related to natural or anthropogenic factors. The data support multiple hypotheses: that carbonate bedrock increases infiltration, subsurface flow, or sediment supply, and therefore creates shallower channels or that cleared land increases erosion and sediment supply, which fills in channels (table 1).

### Current River System

Relations between drainage-basin scale and reach-geometry variables are less consistent in the Current River system. Perhaps because of localized geologic differences, there are more outlier drainage basins, and in some cases there are different trends for the two physiographic groups. For example, the Jacks Fork River has unusually large channel dimensions and very few glide habitats, characteristics that may relate to the canyon-like morphology of this section of the river (McKenney, 1997; Panfil and Jacobson, 1999). Igneous rocks also have a localized affect that is difficult to quantify – several of the Middle Current drainage basins (Shawnee, Mill, and Rocky Creeks) have unusual elevation ranges, substrate, and hydrology because of igneous rocks at or near the landscape's surface (fig. 15).

There are also clear differences between the two Current River groups. For example, after accounting for differences in drainage area, multiple-regression models show that reach gradient is positively associated with elevation range and negatively associated with drainage-basin average slope (table 15). This relation is unexpected because the two relief variables are correlated; basins with steep slopes also have high elevation ranges (table 8). It is also unexpected because the model suggests that basins with steeper slopes have lower gradient streams than basins with shallower slopes – one would expect higher gradient streams in more rugged terrain. However, the regression model is also significant when an indicator variable specifying

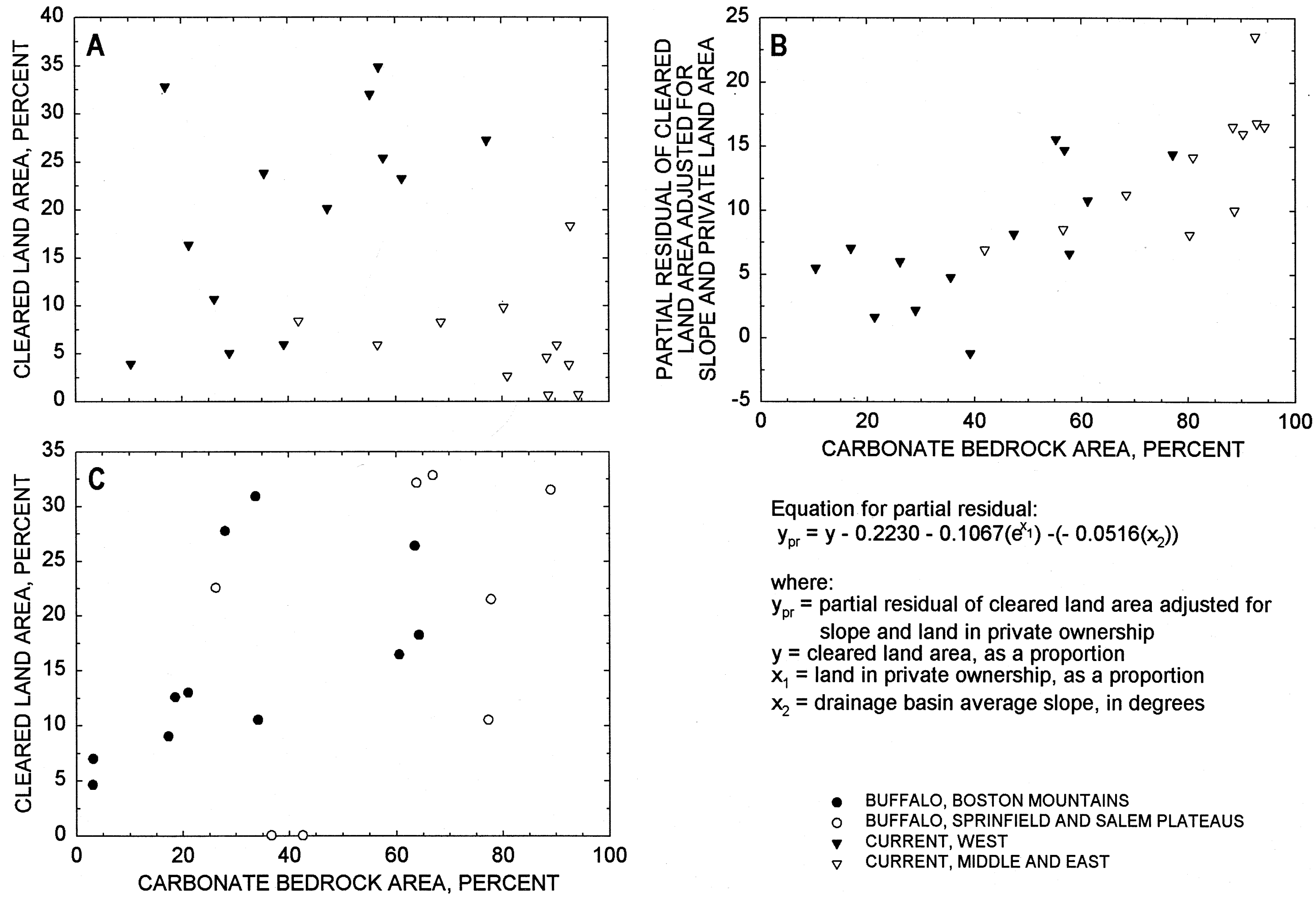



**Figure 25.** A. Scatter plot showing the relation between cleared land area and carbonate bedrock area in the Current River system. B. Partial residual plot for the Current River system after adjusting for differences in slope and private land area. The partial residual was derived from the regression model shown in Table 9 using the method outlined in Ramsey and Schafer (1996). C. Scatter plot showing the relation between cleared land area and carbonate bedrock area in the Buffalo River system.

**Table 10.** Summary statistics for reach-geometry variables

[m, meters; refer to Table 5 for variable definitions]

| Variable | Mean | Standard deviation | Median | Minimum | Maximum |
|---|---|---|---|---|---|
| **Both River Systems, n = 36** | | | | | |
| Reach gradient | 0.00374 | 0.00242 | 0.0031 | 0.0009 (Richland) | 0.0106 (Middle) |
| Average bankfull width (m) | 20.9 | 7.2 | 18.1 | 12.4 (Rogers) | 37.5 (Jacks Fork) |
| Average bankfull depth (m) | 0.80 | 0.22 | 0.75 | 0.47 (Bay) | 1.50 (Richland) |
| Average residual pool depth (m) | 0.38 | 0.17 | 0.36 | 0.15 (Middle) | 0.95 (Jacks Fork) |
| Average residual pool length (m) | 77.9 | 52.8 | 61.1 | 21.4 (Middle) | 258.1 (Cave) |
| Residual pools (percent) | 77 | 14 | 79 | 43 (Rush) | 95 (Richland) |
| Glides (percent) | 31 | 10 | 33 | 5 (Jacks Fork) | 50 (Spring Valley) |
| Obstruction pools (percent) | 15 | 17 | 9 | 0 (many) | 64 (Brush) |
| Pools (percent) | 31 | 12 | 30 | 10 (Brush) | 52 (Jacks Fork) |
| **Buffalo River System, n = 19** | | | | | |
| Reach gradient | 0.00423 | 0.00282 | 0.0041 | 0.0009 (Richland) | 0.0106 (Middle) |
| Average bankfull width (m) | 22.1 | 7.9 | 19.4 | 13.9 (Brush) | 36.4 (Big (upper) |
| Average bankfull depth (m) | 0.89 | 0.24 | 0.85 | 0.50 (Brush) | 1.50 (Richland) |
| Average residual pool depth (m) | 0.36 | 0.17 | 0.32 | 0.15 (Middle) | 0.80 (Richland) |
| Average residual pool length (m) | 87.6 | 65.9 | 65.2 | 21.4 (Middle) | 258.1 (Cave) |
| Residual pools (percent) | 70 | 16 | 75 | 43 (Rush) | 95 (Richland) |
| Glides (percent) | 28 | 8 | 31 | 12 (Leatherwood) | 44 (Clabber) |
| Obstruction pools (percent) | 9 | 16 | 0 | 0 (many) | 64 (Brush) |
| Pools (percent) | 29 | 14 | 22 | 10 (Brush) | 50 (Little Buffalo) |
| **Current River System, n = 17** | | | | | |
| Reach gradient | 0.00319 | 0.00181 | 0.0024 | 0.0016 (Sinking) | 0.009 (Bay) |
| Average bankfull width (m) | 19.6 | 6.4 | 17.5 | 12.4 (Rogers) | 37.5 (Jacks Fork) |
| Average bankfull depth (m) | 0.71 | 0.15 | 0.73 | 0.47 (Bay) | 0.91 (Jacks Fork, Sinking) |
| Average residual pool depth (m) | 0.40 | 0.18 | 0.36 | 0.25 (Shawnee) | 0.95 (Jacks Fork) |
| Average residual pool length (m) | 67.0 | 31.5 | 58.3 | 31.6 (Carr) | 153.3 (Jacks Fork) |
| Residual pools (percent) | 84 | 6 | 83 | 75 (Rocky) | 94 (Spring Valley) |
| Glides (percent) | 34 | 10 | 35 | 5 (Jacks Fork) | 50 (Spring Valley) |
| Obstruction pools (percent) | 22 | 17 | 23 | 0 (Big West, Jacks Fork, Rocky) | 62 (Big East) |
| Pools (percent) | 33 | 10 | 31 | 14 (Rocky) | 52 (Jacks Fork) |

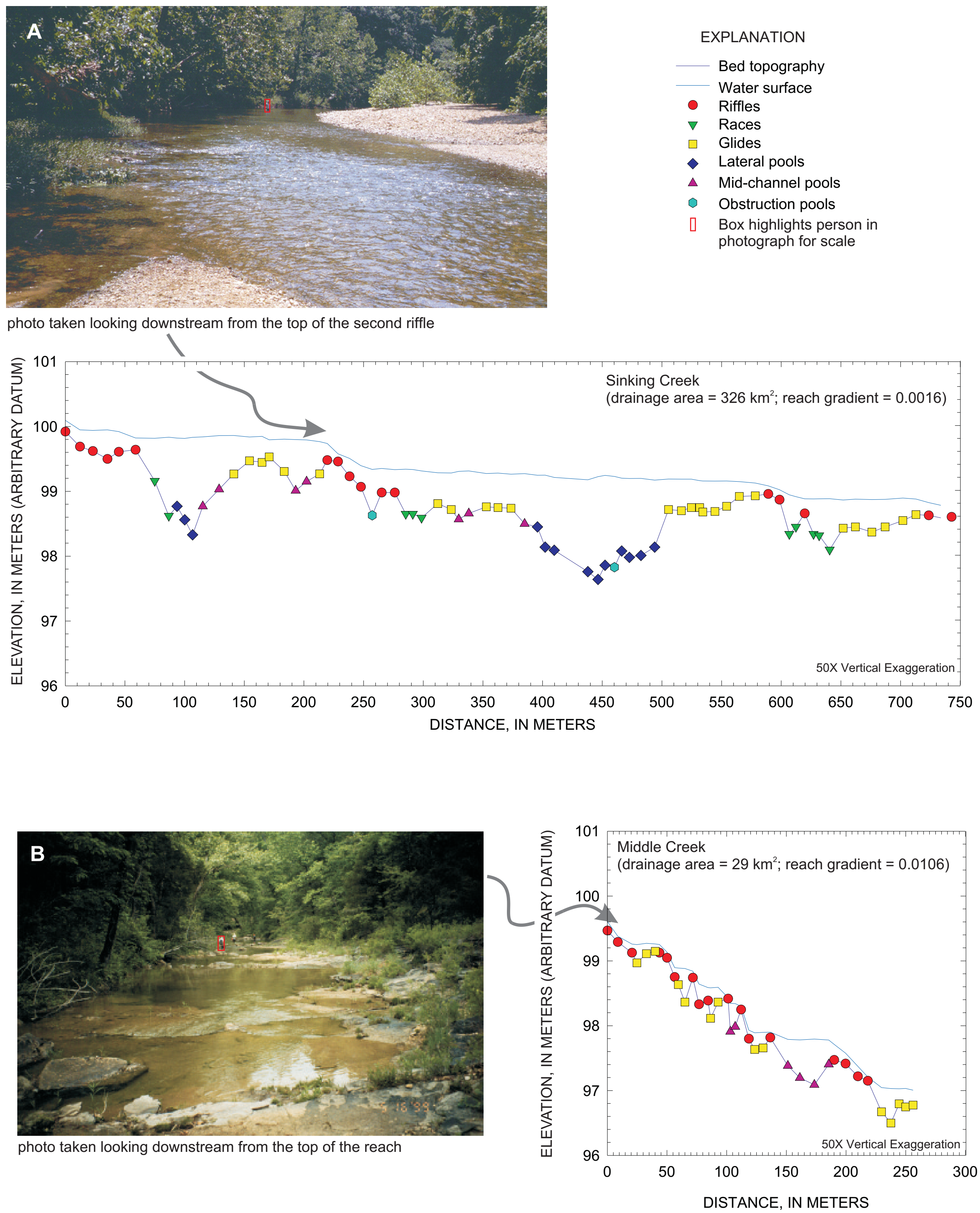



**Figure 26.** Example longitudinal profiles. A. Sinking Creek, a Current River tributary, that is representative of many of the streams in the study. It has a pool-riffle morphology and gravel and cobble dominated substrate. B. Middle Creek, a Buffalo River tributary that is an example of one of the smallest streams in the study. It has a step-pool morphology with a bedrock dominated channel.

**Table 11.** Spearman rank correlation coefficients for relations between reach-geometry variables

[shaded values significant at $p \leq 0.05$; bold values > 0.5 or < -0.5; refer to Table 5 for variable definitions]

| Variable | Reach gradient | Average bankfull width | Average bankfull depth | Average residual pool depth | Average residual pool length | Residual pools | Glides | Obstruction pools | Pools |
|---|---|---|---|---|---|---|---|---|---|
| **Both River Systems, n = 36** | | | | | | | | | |
| Reach gradient | **1.00** | | | | | | | | |
| Average bankfull width | **-0.79** | **1.00** | | | | | | | |
| Average bankfull depth | **-0.53** | **0.66** | **1.00** | | | | | | |
| Average residual pool depth | **-0.56** | **0.63** | 0.44 | **1.00** | | | | | |
| Average residual pool length | **-0.78** | **0.75** | **0.65** | **0.61** | **1.00** | | | | |
| Residual pools | **-0.74** | **0.56** | 0.35 | **0.58** | **0.51** | **1.00** | | | |
| Glides | -0.29 | 0.13 | 0.11 | -0.01 | 0.11 | **0.51** | **1.00** | | |
| Obstruction pools | 0.08 | -0.30 | **-0.52** | -0.30 | -0.31 | 0.04 | 0.20 | **1.00** | |
| Pools | **-0.60** | **0.53** | 0.43 | **0.70** | **0.65** | **0.66** | -0.09 | -0.23 | **1.00** |
| **Buffalo River System, n = 19** | | | | | | | | | |
| Reach gradient | **1.00** | | | | | | | | |
| Average bankfull width | **-0.85** | **1.00** | | | | | | | |
| Average bankfull depth | **-0.61** | **0.78** | **1.00** | | | | | | |
| Average residual pool depth | **-0.68** | **0.79** | **0.72** | **1.00** | | | | | |
| Average residual pool length | **-0.81** | **0.79** | **0.69** | **0.80** | **1.00** | | | | |
| Residual pools | **-0.71** | **0.84** | **0.81** | **0.76** | **0.65** | **1.00** | | | |
| Glides | -0.09 | 0.27 | 0.41 | 0.06 | 0.03 | 0.30 | **1.00** | | |
| Obstruction pools | 0.12 | -0.21 | -0.34 | -0.15 | -0.19 | -0.40 | -0.06 | **1.00** | |
| Pools | **-0.68** | **0.71** | **0.71** | **0.80** | **0.79** | **0.80** | -0.04 | **-0.53** | **1.00** |
| **Current River System, n = 17** | | | | | | | | | |
| Reach gradient | **1.00** | | | | | | | | |
| Average bankfull width | **-0.78** | **1.00** | | | | | | | |
| Average bankfull depth | **-0.67** | **0.57** | **1.00** | | | | | | |
| Average residual pool depth | -0.33 | 0.44 | 0.22 | **1.00** | | | | | |
| Average residual pool length | **-0.82** | **0.76** | **0.69** | 0.30 | **1.00** | | | | |
| Residual pools | **-0.66** | **0.58** | 0.40 | 0.32 | 0.48 | **1.00** | | | |
| Glides | -0.45 | 0.27 | 0.17 | -0.12 | 0.32 | **0.64** | **1.00** | | |
| Obstruction pools | 0.26 | -0.26 | -0.33 | **-0.66** | -0.31 | -0.03 | 0.09 | **1.00** | |
| Pools | -0.33 | 0.30 | 0.19 | 0.32 | 0.37 | 0.28 | -0.18 | -0.11 | **1.00** |

**Table 12.** Spearman rank correlation coefficients for relations between reach-geometry variables and drainage-basin variables

[shaded values significant at p ≤ 0.05; bold values > 0.5 or < -0.5; refer to Table 5 for variable definitions]

| Variable | Carbonate bedrock area | Drainage area | Drainage basin shape | Elevation range | Drainage basin average slope | Bluff area in stream buffer | Cleared land area | Steep, cleared land area | Cleared land in stream buffer | Road density | Road density in stream buffer |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Both River Systems, n = 36** | | | | | | | | | | | |
| Reach gradient | 0.13 | **-0.83** | -0.17 | -0.11 | 0.13 | -0.15 | -0.20 | -0.06 | -0.39 | -0.32 | -0.21 |
| Average bankfull width | -0.35 | **0.77** | -0.02 | 0.25 | 0.02 | 0.32 | 0.24 | 0.26 | 0.31 | 0.02 | -0.02 |
| Average bankfull depth | -0.50 | **0.51** | -0.22 | 0.47 | 0.26 | 0.46 | -0.01 | 0.13 | -0.02 | -0.23 | -0.14 |
| Average residual pool depth | -0.35 | **0.51** | -0.05 | 0.16 | 0.05 | 0.35 | -0.14 | -0.24 | -0.07 | -0.01 | 0.06 |
| Average residual pool length | -0.27 | **0.62** | 0.07 | 0.23 | 0.18 | 0.40 | -0.01 | 0.03 | 0.04 | 0.03 | 0.08 |
| Residual pools | -0.19 | **0.75** | 0.21 | -0.20 | -0.27 | 0.11 | 0.01 | -0.33 | 0.28 | 0.05 | 0.06 |
| Glides | -0.01 | 0.32 | 0.32 | -0.31 | -0.36 | -0.06 | 0.17 | -0.17 | 0.29 | 0.02 | -0.11 |
| Obstruction pools | 0.28 | -0.07 | 0.20 | -0.40 | -0.35 | -0.43 | 0.06 | -0.13 | 0.31 | 0.39 | 0.23 |
| Total pools | -0.16 | 0.47 | 0.00 | 0.09 | 0.12 | 0.21 | -0.26 | -0.33 | -0.06 | 0.03 | 0.18 |
| **Buffalo River System, n = 19** | | | | | | | | | | | |
| Reach gradient | 0.21 | **-0.81** | -0.29 | **-0.60** | 0.09 | -0.13 | -0.17 | -0.06 | -0.48 | -0.41 | -0.41 |
| Average bankfull width | -0.47 | **0.87** | 0.14 | **0.61** | 0.00 | 0.31 | 0.00 | -0.08 | 0.40 | 0.06 | 0.16 |
| Average bankfull depth | **-0.66** | **0.59** | -0.05 | 0.49 | 0.23 | 0.41 | -0.27 | -0.36 | 0.09 | -0.09 | -0.02 |
| Average residual pool depth | **-0.59** | **0.65** | -0.12 | **0.68** | 0.32 | 0.47 | -0.35 | -0.39 | 0.03 | 0.05 | 0.27 |
| Average residual pool length | -0.41 | **0.65** | 0.30 | **0.58** | 0.26 | 0.32 | -0.19 | -0.27 | 0.16 | 0.14 | 0.25 |
| Residual pools | **-0.56** | **0.79** | 0.02 | **0.63** | 0.04 | 0.41 | -0.08 | -0.18 | 0.34 | -0.02 | 0.07 |
| Glides | -0.28 | 0.17 | 0.18 | -0.01 | -0.22 | -0.01 | 0.03 | -0.04 | 0.11 | -0.13 | -0.29 |
| Obstruction pools | 0.28 | -0.09 | 0.01 | 0.10 | -0.22 | -0.16 | 0.16 | 0.19 | 0.19 | 0.36 | 0.24 |
| Total pools | **-0.53** | **0.52** | 0.07 | **0.55** | 0.28 | 0.35 | -0.29 | -0.44 | -0.01 | -0.06 | 0.11 |
| **Current River System, n = 17** | | | | | | | | | | | |
| Reach gradient | 0.12 | **-0.83** | 0.10 | 0.04 | 0.22 | -0.21 | -0.30 | -0.41 | -0.16 | -0.10 | 0.25 |
| Average bankfull width | -0.21 | **0.68** | -0.03 | -0.13 | -0.12 | 0.41 | 0.30 | 0.49 | 0.14 | -0.09 | -0.28 |
| Average bankfull depth | -0.13 | **0.72** | -0.28 | 0.16 | -0.20 | 0.21 | 0.18 | 0.22 | 0.07 | -0.32 | -0.16 |
| Average residual pool depth | -0.18 | 0.28 | -0.01 | 0.14 | -0.07 | 0.40 | -0.03 | -0.15 | -0.28 | -0.24 | -0.22 |
| Average residual pool length | -0.04 | **0.65** | -0.12 | -0.01 | -0.02 | 0.44 | 0.16 | 0.43 | 0.01 | -0.05 | -0.17 |
| Residual pools | -0.28 | **0.64** | 0.14 | -0.13 | -0.37 | 0.22 | 0.32 | 0.12 | 0.09 | -0.21 | -0.33 |
| Glides | -0.09 | 0.44 | 0.42 | -0.05 | -0.30 | 0.27 | 0.48 | 0.33 | 0.38 | 0.17 | -0.11 |
| Obstruction pools | 0.01 | -0.17 | 0.25 | -0.28 | 0.03 | -0.49 | 0.03 | 0.10 | 0.25 | 0.37 | 0.16 |
| Total pools | 0.37 | 0.25 | -0.07 | 0.15 | 0.18 | 0.15 | -0.21 | -0.10 | -0.22 | -0.07 | -0.04 |

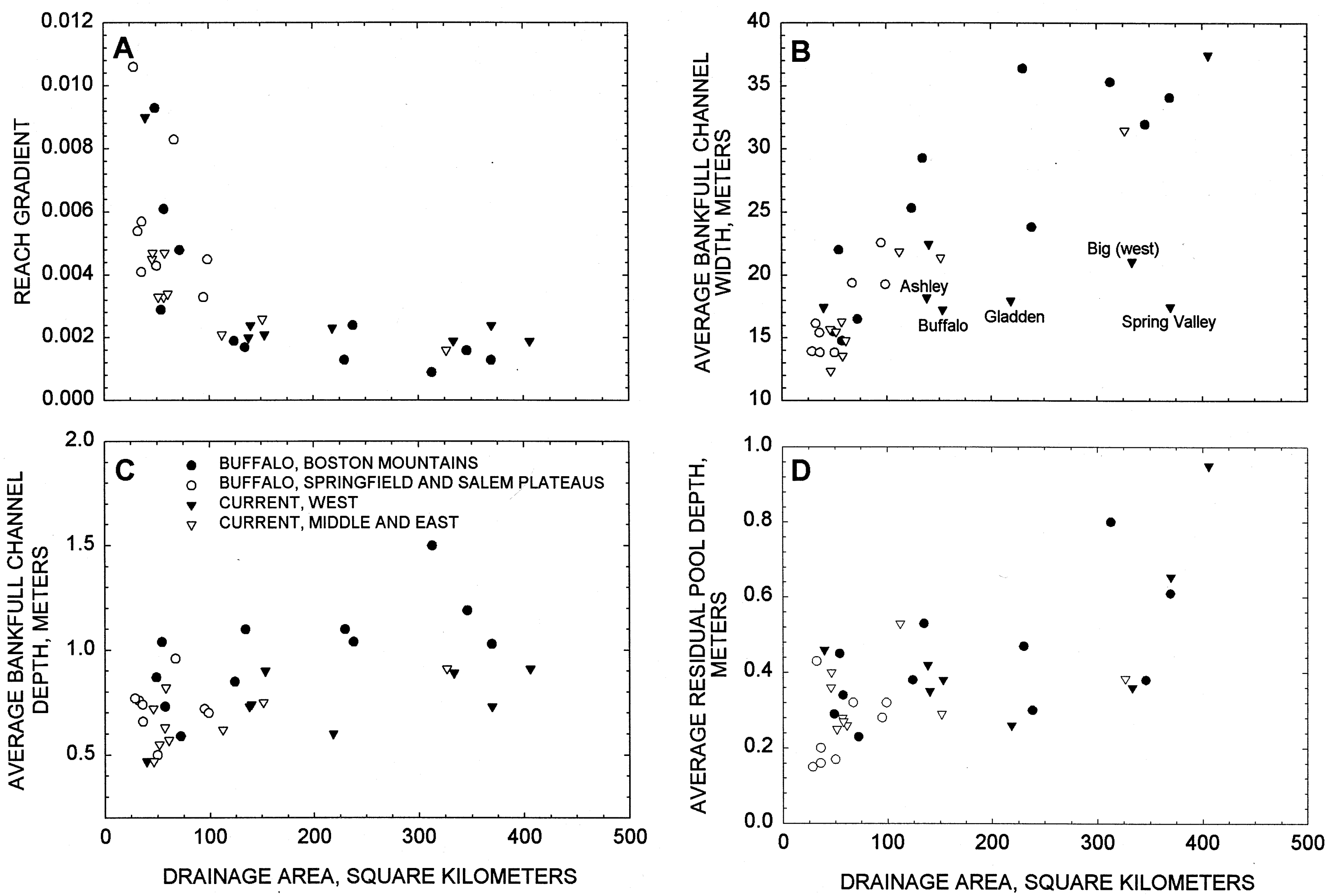



**Figure 27.** Scatter plots of drainage area and channel geometry variables including: A. reach gradient, B. average bankfull channel width, C. average bankfull channel depth, D. average residual pool depth, E. average residual pool length, F. the proportion of reach length with pool habitats, G. the proportion of reach length with glide habitats, and H. the proportion of the reach length within residual pools.

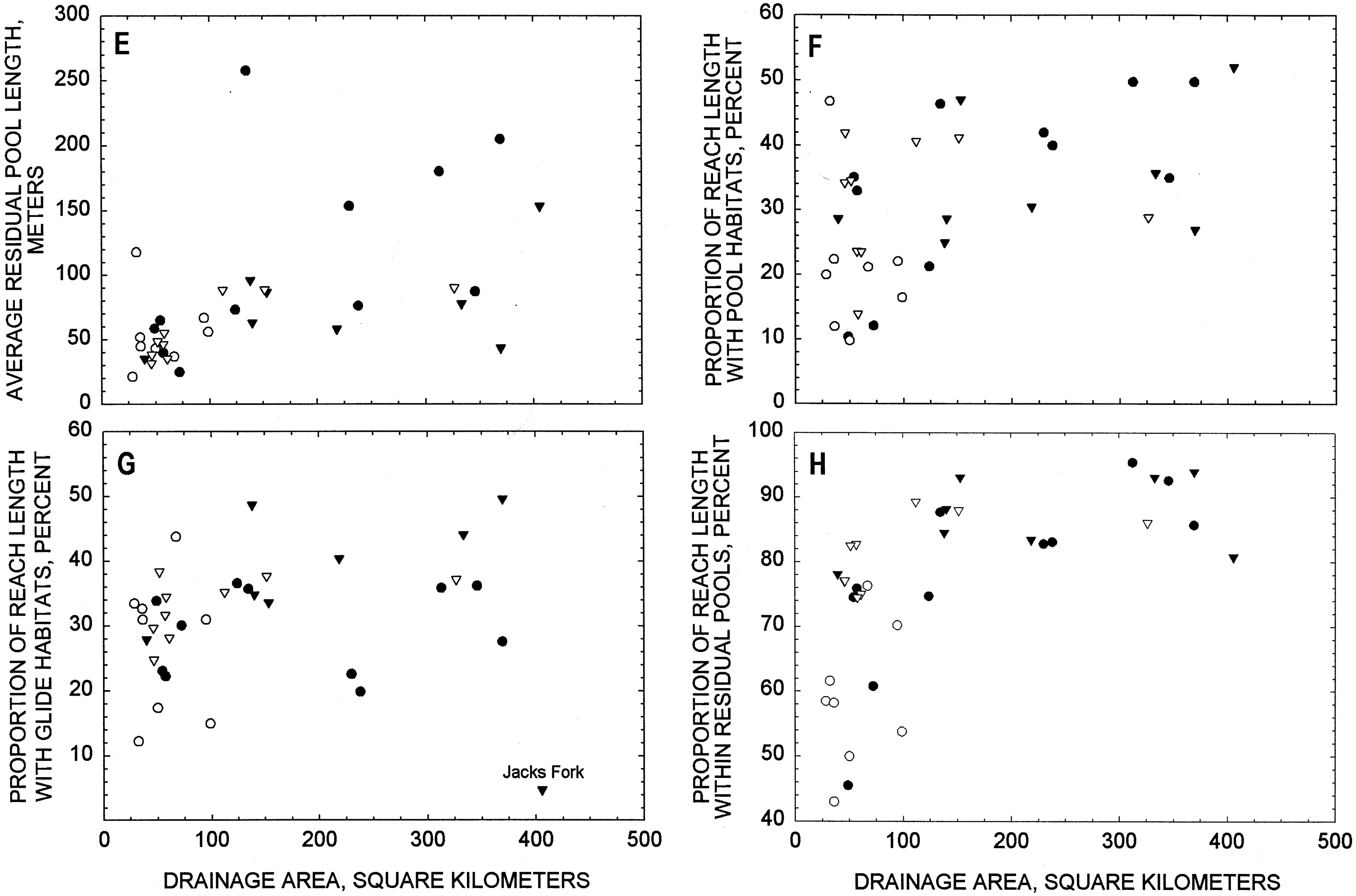



**Figure 27 continued:** Scatter plots of drainage area and channel geometry variables including: A. reach gradient, B. average bankfull channel width, C. average bankfull channel depth, D. average residual pool depth, E. average residual pool length, F. the proportion of reach length with pool habitats, G. the proportion of reach length with glide habitats, and H. the proportion of the reach length within residual pools.

drainage-basin group is substituted for drainage-basin average slope (table 15). Slope is the main physiographic characteristic that divides the groups; steep hillslopes are concentrated in the middle and east Current drainage basins (fig. 19A). Differences in karst hydrology between the two physiographic groups may explain the unusual inverse relation between drainage-basin average slope and reach gradient. The west Current drainage basins have more underdrained streams and more extensive karst networks than the middle and east group – it is possible that reduced transport capacity in karst streams results in aggradation and steeper reach gradients compared to non-karst streams.

Regression models for bankfull channel widths also suggest a relation between karst hydrology and channel geometry in the Current River system (table 15). Bankfull width is positively associated with drainage-basin average slope and negatively associated with drainage-basin shape when the model accounts for differences in drainage area. On inspection of scatter and partial residual plots, it appears that this model may also be related to the distribution of karst networks in the drainage basin. Tributaries with narrow channel widths for their drainage area are in the west Current and tend to have extensive karst systems and underdrained streams (for example, Spring Valley, Big (west), Gladden Creek; fig. 27B). Perhaps by coincidence, these basins also tend to be longer and narrower and therefore have higher values for drainage-basin shape.

We also found several significant models relating basin-scale variables to the proportion of residual pools within the study reaches. The proportion of residual pools measures the proportional distance between riffles, streams with many or long riffles will have a low proportion of residual pools (fig. 5). Studies of the relation between channel form and sediment supply suggest that the proportion of residual pools may relate to this balance (Montgomery and Buffington, 1996; Montgomery and others, 1999). As sediment supply increases, channels tend to have smoother channel morphologies with less residual pool; they shift from pool-riffle channels to plane bed channels to braided systems. This change in morphology creates a positive feedback mechanism between sediment supply and transport capacity. In smoother channels, less energy is dissipated to longitudinal roughness elements and therefore transport capacity is increased.

This model of the relation between longitudinal channel geometry and sediment supply may help explain differences in the proportion of residual pools in the Current's two physiographic groups. Scatter plots and multiple regression show that the proportion of residual pools increases as drainage-basin average slope decreases in the west Current drainage basins while the opposite trend is true in the middle and east Current (fig. 31A, table 15). Steeper slopes appear to have different effects in the two physiographic groups – in the East Current, they appear to create more scour and a greater proportion of residual pools while in the west Current they appear to increase sediment supply and the proportion of riffles. These relations may relate to the dual effect of steep slopes. They have the potential to increase both sediment supply and transport capacity – steep slopes may increase runoff and storm discharges and steep slopes may facilitate sediment entrainment and transport (table 1). In the west Current, where the high proportion of karst hydrology diverts run-off to the subsurface, an increase in drainage-basin average slope may increase sediment supply faster than it increases transport capacity. In streams, this would create smoother longitudinal channel morphologies with long riffles and a low proportion of residual pools. In the steep, drainage basins of the east Current, an increase in drainage-basin average slope may increase transport capacity faster than it increases sediment supply. This would create streams capable of scouring and developing a large proportion of residual pools.

This hypothesis is also consistent with the Buffalo River system's negative relation between the proportion of residual pools, carbonate bedrock area, and cleared land area (table 14). Carbonate bedrock has the potential to increase sediment supply relative to transport capacity by improving infiltration, reducing storm flow, and increasing the supply of chert gravel to streams (table 1). At the same time, greater areas of pasture and cleared land have the potential to increase erosion and sediment supply (table 1). In accordance with our residual-pool conceptual model, a higher sediment supply would translate into a smooth bed with a low proportion of residual pools relative to riffles. We found a similar relation with cleared land area for drainage basins in the west Current. After accounting for differences in drainage area and slope, the proportion of residual pools is negatively associated with cleared land area (fig. 31B, C).

Drainage basins in the Current also show a relation between the proportion of cleared land and the proportion of glide habitats. After accounting for differences in drainage area, the proportion of glides is positively associated with cleared land area, steep, cleared land area, or cleared land area in stream buffers. As in other regression models, the three correlated land cover variables act as proxies for each other, when one is in the model the other variables are not significant. These models do not, however, account for differences in drainage-basin average slope or differences between the middle and east and west Current drainage-basin groups. Without this difference accounted for it remains

**Table 13.** Selected multiple regression models for reach-geometry variables and all study drainage basins; explanatory variables significant at $p \leq 0.05$; n = 36 unless specified

[m, meters; $m^2$, square meters]

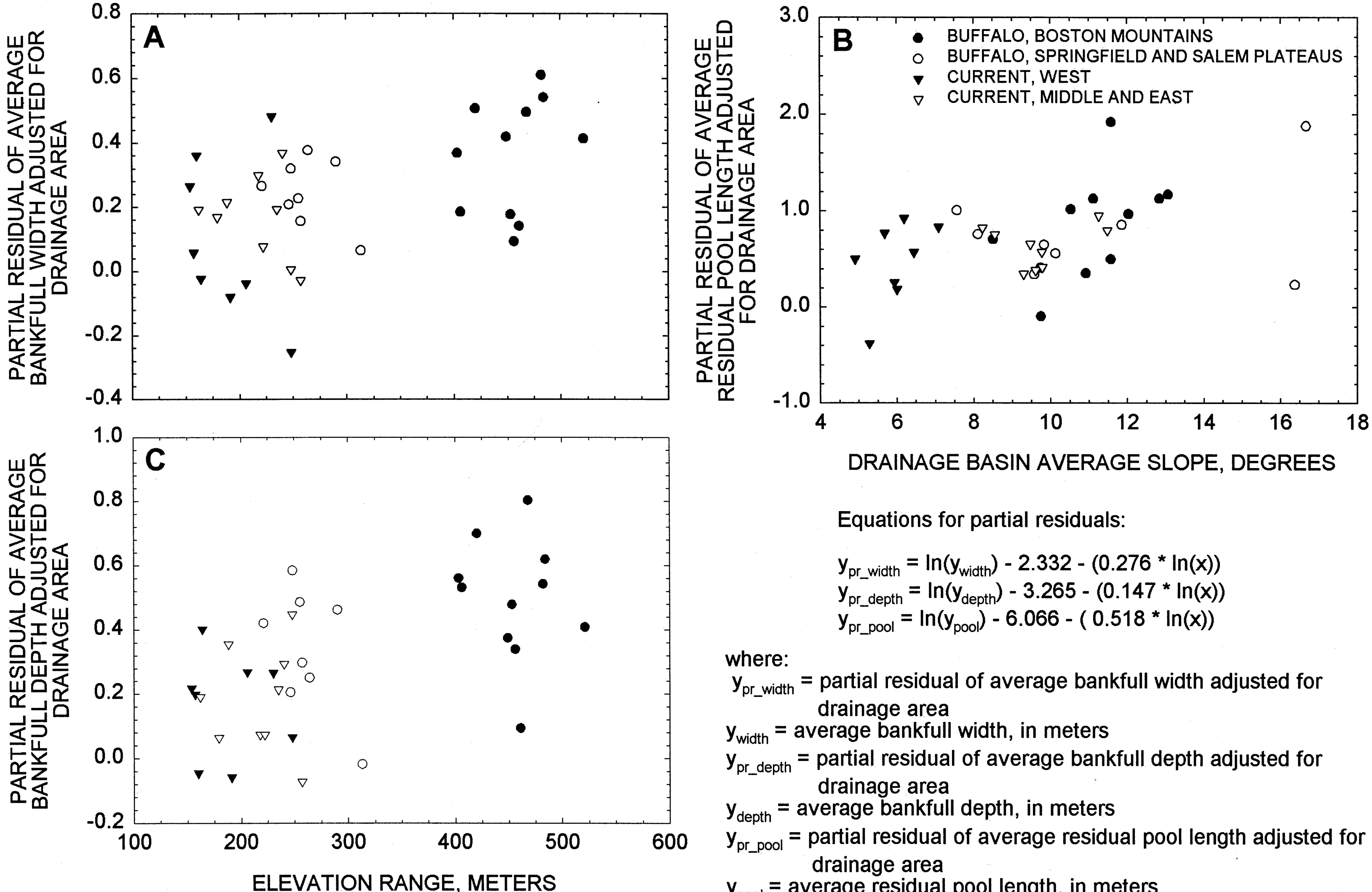
| Response variable | Intercept | Indicator for river system[1] | Model coefficients for explanatory variables: Geology | Physiography | | | | | Land use | | | R squared |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Carbonate bedrock area, as a proportion | Drainage area,[2] in $m^2$ | Drainage basin shape | Elevation range, in m | Drainage basin average slope, in degrees | Bluff area in stream buffer, as a proportion[3] | Cleared land area, as a proportion | Steep, cleared land, as a proportion | Road density, in $m/m^2$ | |
| Average bankfull width,[2] in m | -2.8032 | -0.1896 | | 0.3189 | | | | | | | | 0.71 |
| | -2.3321 | | | 0.2761 | | 0.0008 | | | | | | 0.70 |
| | -3.5404 | | | 0.3358 | | | 0.0349 | | | | | 0.71 |
| | -3.6640 | | | 0.3570 | -0.0414 | | 0.0301 | | | | | 0.79 |
| Average bankfull depth,[2] in m | -3.9171 | -0.2683 | | 0.2054 | | | | | | | | 0.57 |
| | -2.9539 | | -0.3986 | 0.1577 | | | | | | | | 0.48 |
| | -3.2649 | | | 0.1465 | | 0.0010 | | | | | | 0.51 |
| | -4.7315 | | | 0.2211 | | | 0.0413 | | | | | 0.48 |
| | -3.2014 | | | 0.1562 | | | | 8.1566 | | | | 0.38 |
| | -3.4284 | | | 0.1936 | | | | | | | -407.934 | 0.42 |
| | -4.3634 | -0.2955 | | 0.2364 | | | | | -0.7088 | | | 0.65 |
| Average residual pool depth,[2] in m | -6.6101 | | | 0.3079 | | | | | | -3.0050 | | 0.47 |
| | -6.9196 | | | 0.3407 | -0.0518 | | | | | -3.4782 | | 0.53 |
| Average residual pool length,[2] in m | -6.0655 | | | 0.5179 | | | 0.0718 | | | | | 0.51 |
| Glides,[4] as a proportion | -0.3837 | 0.0691 | | 0.0365 | | | | | | | | 0.31 |
| | -0.5775 | | | 0.0540 | | -0.0003 | | | | | | 0.33 |
| | -0.0910 | | | 0.0292 | | | -0.0131 | | | | | 0.31 |
| Pools, as a proportion | -1.0271 | | | 0.0723 | | | | | | | | 0.24 |
| | -1.3102 | | | 0.0919 | | | | | -0.4905 | | | 0.43 |

[1] Indicator variable specifies river system, Buffalo = 0 or Current = 1.

[2] Variables were transformed, ln(x).

[3] Variable was transformed, squareroot(x).

[4] These models exclude Jacks Fork.




Equations for partial residuals:

$$y_{pr\_width} = \ln(y_{width}) - 2.332 - (0.276 * \ln(x))$$
$$y_{pr\_depth} = \ln(y_{depth}) - 3.265 - (0.147 * \ln(x))$$
$$y_{pr\_pool} = \ln(y_{pool}) - 6.066 - (0.518 * \ln(x))$$

where:
$y_{pr\_width}$ = partial residual of average bankfull width adjusted for drainage area
$y_{width}$ = average bankfull width, in meters
$y_{pr\_depth}$ = partial residual of average bankfull depth adjusted for drainage area
$y_{depth}$ = average bankfull depth, in meters
$y_{pr\_pool}$ = partial residual of average residual pool length adjusted for drainage area
$y_{pool}$ = average residual pool length, in meters
x = drainage area, in square meters

**Figure 28.** Partial residual plots showing the relation between channel-geometry variables and relief variables after accounting for differences in drainage area. The partial residuals were derived from the regression models shown above and in Table 13 using the method outlined in Ramsey and Schafer (1996).

**Figure 29.** Photograph of Spring Valley Creek, one of the west Current tributaries affected by karst hydrology. It has one of the larger drainage areas among the Current River tributaries (369 km$^2$), yet its channel morphology is that of a smaller stream. The channel in this picture (May 1999) is completely dry much of the year.

difficult to differentiate between anthropogenic and natural factors.

## Substrate

In general, gravel and cobble/boulder substrates are the most abundant in the study reaches. Along the thalweg surveys, the average proportions of gravel and cobble/boulders were 59 and 28 percent respectively (table 16). In glides, where pebble count data were collected, the mean particle size (D50) was 32 mm, coarse gravel in the modified Wentworth scale (Fitzpatrick and others, 1998). Two streams in the Buffalo River system, Cecil and Richland Creeks, have unusually coarse substrate and little gravel throughout the reach (fig. 32; fig. 33). Sand and mud were the least common substrates and embeddedness both in glides and along thalwegs was generally low. The exception was Gladden Creek (fig. 32B), where sand covered most of the channel bed and caused the creek to plot as an outlier for many substrate measurements.

In general, drainage basins in the Current tend to have finer substrates and less bedrock than those in the Buffalo River system (table 16); they tended to have a greater proportions of gravel recorded along the thalweg, more embeddedness, and smaller grain sizes recorded in glides and on point bars.

Nearly all Buffalo reach surveys recorded some bedrock along the thalweg with the highest proportion recorded at 49 percent in Middle Creek (fig. 26B). The exception to the scarcity of bedrock in the Current was Rocky Creek, where 19 percent of the surveyed thalweg had a bedrock substrate. This characteristic likely relates to the high proportion of igneous bedrock in the Rocky Creek drainage basin and through the study reach.

Correlation analysis showed consistency among the

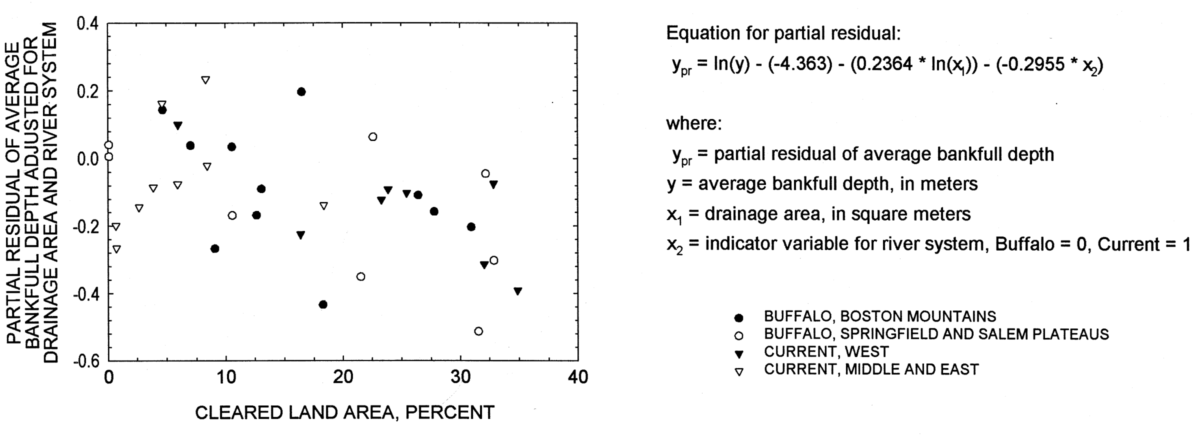



**Figure 30.** Partial residual plot showing the relation between average bankfull depth and cleared land area after accounting for differences in drainage area and river system. The partial residuals were derived from the regression models shown in Table 13 using the method outlined in Ramsey and Schafer (1996).

**Table 14.** Selected multiple regression models for reach-geometry variables and Buffalo River tributaries; explanatory variables signficant at $p \leq 0.05$ and $n = 19$ unless specified

[m, meters; $m^2$, square meters]

| | | Model coefficients for explanatory variables | | | | | |
|---|---|---|---|---|---|---|---|
| | | Geology | Physiography | Land use | | | |
| Response variable | Intercept | Carbonate bedrock area, as a proportion | Drainage area,[1] in $m^2$ | Cleared land area, as a proportion | Steep, cleared land area, as a proportion | Cleared land in stream buffer, as a proportion | R squared |
| Average bankfull depth,[1] in m | -3.0841 | -0.4657 | 0.1710 | | | | 0.66 |
| | -4.3441 | | 0.2369 | -0.8766 | | | 0.60 |
| | -4.2711 | | 0.2344 | | -2.7998 | | 0.70 |
| | -5.2219 | | 0.2847 | | | -0.9314 | 0.61 |
| Average residual pool depth,[1] in m | -6.2595 | -0.6897 | 0.2968 | | | | 0.61 |
| | -8.1953 | | 0.4027 | -1.7634 | | | 0.66 |
| | -8.0294 | | 0.3934 | | -4.7205 | | 0.69 |
| | -9.7047 | | 0.4826 | | | -1.6370 | 0.61 |
| Residual pools, as a proportion[2] | -2.8778 | -0.4299 | 0.1479 | | | | 0.78 |
| | -4.1021 | | 0.2095 | | -1.5867 | | 0.71 |
| Pools, as a proportion | -1.0313 | -0.2024 | 0.0768 | | | | 0.47[3] |
| | -1.5567 | | 0.1065 | | -1.6769 | | 0.63 |

[1] Variables were transformed, ln(x).

[2] Beech excluded.

[3] Beech and Leatherwood excluded.

**Table 15.** Selected multiple regression models for reach-geometry variables and Current River tributaries; explanatory variables signficant at $p \leq 0.05$ and n = 17 unless specified

[m, meters; $m^2$, square meters]

| Response variable | Intercept | Indicator for physiographic group[1] | Model coefficients for explanatory variables: Physiography | | | | Land use | | | Interaction | R squared |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Drainage area,[2] in $m^2$ | Drainage basin shape factor | Elevation range, in m | Drainage basin average slope, in degrees | Cleared land area, as a proportion | Steep, cleared land area, as a proportion | Cleared land in stream buffer, as a proportion | Product of drainage basin average slope and indicator for physiographic group | |
| Reach gradient | 0.8899 | | -0.3979 | | 0.0029 | | | | | | 0.83[3] |
| | 2.6561 | | -0.4860 | | 0.0046 | -0.0583 | | | | | 0.91[3] |
| | 3.3422 | -0.2935 | -0.5417 | | 0.0048 | | | | | | 0.90[3] |
| | 2.5280 | | -0.4947 | | 0.0052 | -0.0507 | | | 0.4726 | | 0.93[3] |
| Average bankfull width,[2] in m | -2.1035 | | 0.2847 | -0.0425 | | | | | | | 0.66 |
| | -3.4591 | | 0.3404 | -0.0533 | | 0.0486 | | | | | 0.77 |
| Residual pools, as a proportion | 0.5016 | -0.6451 | 0.0386 | | | -0.0617 | | | | 0.0880 | 0.76 |
| | 0.3273 | | 0.0568 | | | -0.0765 | -0.3443 | | | | 0.92[4] |
| | 0.2189 | | 0.0635 | | | -0.0804 | | | -0.3293 | | 0.95[4] |
| Glides, as a proportion | -0.6355 | | 0.0521 | | | | 0.2226 | | | | 0.68[5] |
| | -0.8999 | | 0.0665 | | | | | 2.6269 | | | 0.69[5] |
| | -0.8261 | | 0.0622 | | | | | | 0.1692 | | 0.66[5] |

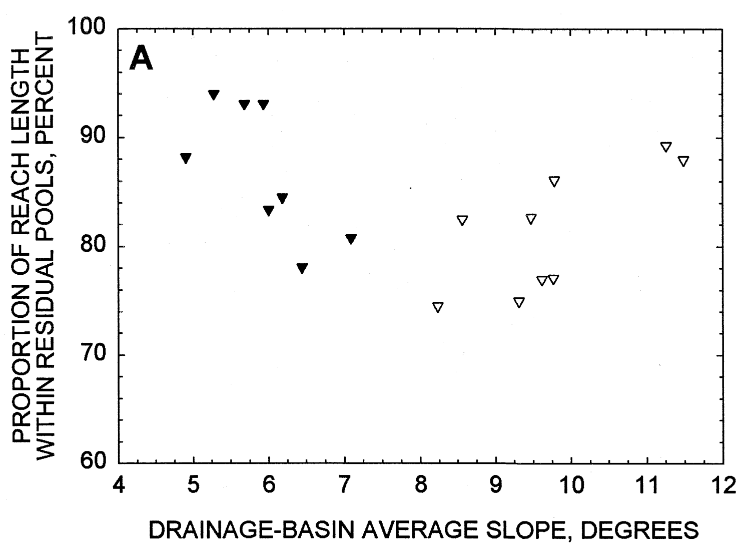
[1] Indicator variable specifies physiographic group, West Current = 0 or Middle and East Current = 1.

[2] Variables were transformed, ln(x).

[3] Models exclude Bay Creek.

[4] Model only significant for West Current basins, n = 8.

[5] Models exclude Jacks Fork,




Equations for partial residuals:

$y_{pr1}$ = y - (0.219) - (0.064 * ln($x_1$)) - (-0.080 * $x_2$)

$y_{pr2}$ = y - (0.327) - (0.057 * ln($x_1$)) - (-0.077 * $x_2$)

where:

$y_{pr1}$ = partial residual for model with cleared land area in stream buffer

y = residual pools, as a proportion of reach length

$y_{pr2}$ = partial residual for model with cleared land area

$x_1$ = drainage area, in square meters

$x_2$ = drainage basin average slope, in degrees

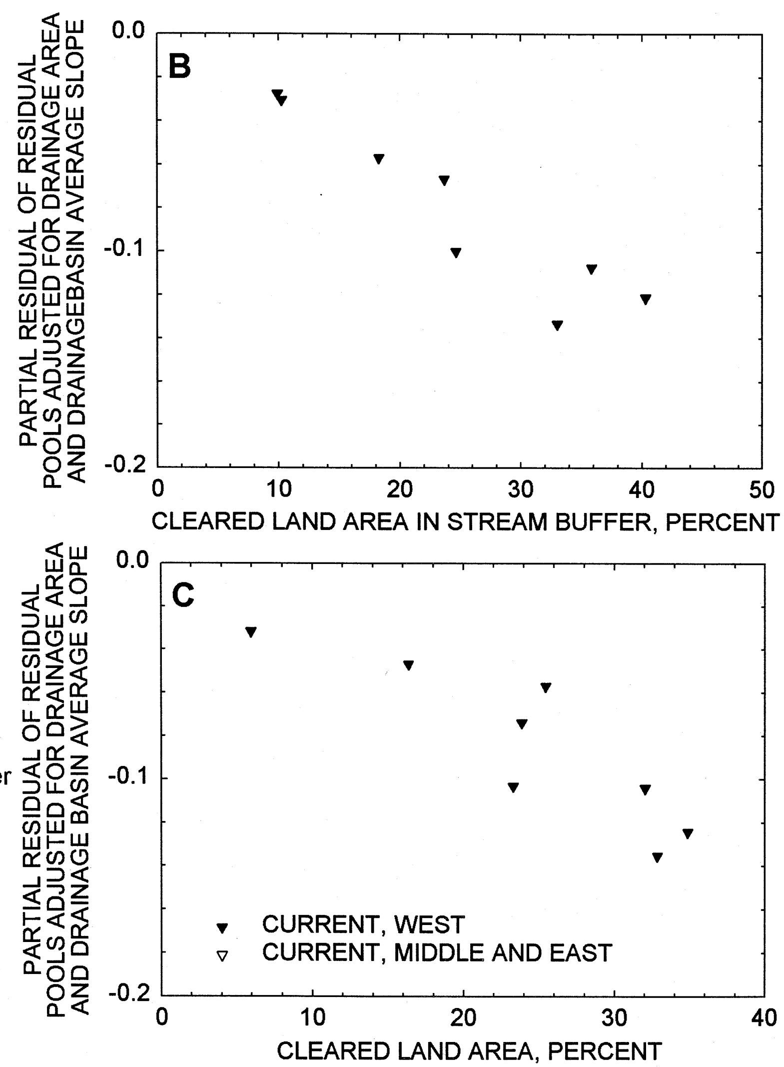



**Figure 31.** Scatter plots showing relations in the Current River system among the proportion of residual pools, drainage-basin average slope, and cleared land area. A. Scatter plot showing opposite trends for the two physiographic groups. B-C. Partial residual plots showing the negative association between residual pools and cleared land area for the west Current group. The partial residuals were derived from the regression models shown in Table 15 using the method outlined by Ramsey and Schafer (1996).

three ways that we measured substrate in each reach: along the thalweg, in glide habitats, and on point bars (table 17). Generally, streams with a large proportion of cobbles and boulders along the thalweg also had larger particle sizes in glides and on point bars. Correlations were weakest between point bar photoseive measurements and other substrate measures, particularly in the Buffalo (table 17). This observation likely relates to the sampling bias of the photoseive method, it was not applied to streams with extremely coarse point bar substrates (cobbles and boulder) because too few particles fit within the 60 cm photo quadrant (fig. 7). Alternately, it may indicate that point-bar particle size is adjusted to different hydrologic events than glide and thalweg particle sizes.

## Relations between Substrate and Drainage-basin Characteristics

### Correlation Analysis

As with the channel geometry measures, correlations are strongest for the combined set of all study drainage basins and for the Buffalo River system (table 18). One striking observation for both of these groups is the lack of relations between substrate measurements and drainage area (fig. 33). In many stream systems, there is a downstream fining trend in which substrate becomes finer as drainage area increases and sediment sources become more distal (table 1). A number of hypotheses may explain the lack of downstream fining including: the many local inputs of sediment from streamside bluffs and small tributaries, the high proportion of chert gravel which tends to be resistant to abrasion and enter streams within a narrow range of sizes, the relatively small size range of the drainage basins (<410 $km^2$), and the geologic and relief differences that may have overwhelmed a downstream fining trend.

Measures of fine substrate also showed few correlations for the combined set of study tributaries. Measures of embeddedness, the percent mud and sand along the thalweg, and the 16th percentile measurements from glides and point bars all showed little relation to most basin-scale variables. This is consistent with the general lack of fine sediment in most study reaches. Sand and embeddedness seemed to be an infrequent, localized phenomenon, that was most common in west Current drainage basins. Of all the study drainage basins, only Gladden Creek showed a high proportion of sand and embeddedness (table 16). It should be noted that within the Current River system, Gladden Creek had one of the highest proportions of cleared land area (tables 3, 7), cleared land area within stream buffers, and one of the lowest drainage-basin average slopes.

Stronger correlations with basin-scale variables were apparent for bedrock and measures of coarse particle sizes than for measures of fine sediment (table 18). In general, drainage basins with high elevation ranges, steep slopes, and a high proportion of streamside bluffs had a high proportion of bedrock, cobbles and boulders along the thalweg, and coarse particle sizes in glides and on point bars (fig. 33; table 18). Correlations with carbonate bedrock area were also apparent; a high proportion of carbonate bedrock was correlated with a high proportion of gravel along the thalweg and small particle sizes in glides.

Correlation analyses also suggested relations between substrate measurements and many land-use variables for the combined set of study drainage basins and for the Buffalo. We used multiple regression to test whether these relations remained significant after accounting for differences in relief and geology.

### Multiple Regression

For the combined set of study drainage basins, we found significant multiple regression models for measures of thalweg and glide substrate (table 19). After accounting for relations with relief variables, the proportion of gravel along the thalweg is positively associated with carbonate bedrock area. Drainage basins with more carbonate bedrock also tend to have less cobble/boulder substrate, even after accounting for differences in relief. This supports the hypothesis that the abundance of chert in Ozarks' carbonates increases the gravel sediment supply to streams (table 1).

After accounting for differences in both relief variables and carbonate bedrock, substrate thalweg measures also show significant relations with some of the land-use variables (table 19). The proportion of gravel is positively associated with cleared land area in stream buffers. Also, the proportion of cobbles and boulders is negatively associated with cleared land area both in buffers and overall. These models support the hypothesis that cleared land and pasture in the Ozarks increase the supply of gravel to streams. Two models also suggest a relation between road density and particle size. However, these models do not include geology as an explanatory variable. The basin-scale analyses show a correlation between carbonate bedrock and road density (table 8) – it is possible that road density is acting as proxy variable for carbonate in these models.

Relations among glide particle size, relief, and land-use variables were consistent with the thalweg substrate trends. An increase in the 84th percentile of glide particle size is associated with an increase in relief elements and a decrease in carbonate bedrock area (table 19). However, models with both carbonate bedrock area and land-use variables are not significant. Instead,

**Table 16.** Summary statistics for reach-substrate variables

[mm, millimeters; refer to Table 5 for variable definitions]

| Variable | Mean | Standard deviation | Median | Minimum | Maximum |
|---|---|---|---|---|---|
| **Both River Systems, n = 36 except point bars where n = 27** | | | | | |
| Bedrock in thalweg (percent) | 9 | 14 | 3 | 0 (many) | 49 (Middle) |
| Mud and sand in thalweg (percent) | 5 | 9 | 0 | 0 (many) | 46 (Gladden) |
| Gravel in thalweg (percent) | 59 | 24 | 55 | 13 (Beech) | 96 (Mill (middle)) |
| Cobbles and boulders in thalweg (percent) | 28 | 21 | 27 | 2 (Gladden) | 72 (Richland) |
| Thalweg embeddedness index | 0.123 | 0.106 | 0.097 | 0 (Middle) | 0.502 (Gladden) |
| Glide embeddedness (percent) | 15 | 16 | 12 | 0 (many) | 82 (Gladden) |
| Glide D16 (mm) | 11 | 5 | 10 | 4 (Gladden) | 21 (Cecil) |
| Glide D50 (mm) | 32 | 19 | 28 | 7 (Gladden) | 105 (Cecil) |
| Glide D84 (mm) | 71 | 41 | 55 | 25 (Gladden) | 207 (Cecil) |
| Glide sorting (Phi) | 1.26 | 0.40 | 1.21 | 0.12 (Calf) | 2.25 (Richland) |
| Point bar D16 (mm) | 12 | 10 | 11 | 5 (Carter, Gladden, Mill) | 58 (Cecil) |
| Point bar D50 (mm) | 33 | 28 | 28 | 10 (Mill) | 157 (Cecil) |
| Point bar D84 (mm) | 61 | 35 | 55 | 15 (Mill) | 194 (Cecil) |
| Point bar sorting (Phi) | 1.13 | 0.19 | 1.11 | 0.76 (Mill) | 1.63 (Mill (upper)) |
| **Buffalo River System, n = 19 except point bars where n = 12** | | | | | |
| Bedrock in thalweg (percent) | 15 | 16 | 7 | 0 (many) | 49 (Middle) |
| Mud and sand in thalweg (percent) | 2 | 3 | 0 | 0 (many) | 10 (Clabber) |
| Gravel in thalweg (percent) | 51 | 26 | 49 | 13 (Beech) | 96 (Mill (middle)) |
| Cobbles and boulders in thalweg (percent) | 32 | 20 | 31 | 4 (Mill (middle)) | 72 (Richland) |
| Thalweg embeddedness index | 0.074 | 0.055 | 0.054 | 0 (Middle) | 0.182 (Cecil) |
| Glide embeddedness (percent) | 11 | 11 | 8 | 0 (Brush, Calf, Mill (middle)) | 37 (Leatherwood) |
| Glide D16 (mm) | 14 | 5 | 14 | 6 (Cave) | 21 (Cecil) |
| Glide D50 (mm) | 42 | 21 | 33 | 26 (Tomahawk) | 105 (Cecil) |
| Glide D84 (mm) | 92 | 43 | 85 | 40 (Tomahawk) | 207 (Cecil) |
| Glide sorting (Phi) | 1.25 | 0.48 | 1.27 | 0.12 (Calf) | 2.25 (Richland) |
| Point bar D16 (mm) | 16 | 14 | 12 | 7 (Mill (upper)) | 58 (Cecil) |
| Point bar D50 (mm) | 44 | 37 | 33 | 23 (Calf) | 157 (Cecil) |
| Point bar D84 (mm) | 76 | 43 | 58 | 43 (Bear) | 194 (Cecil) |
| Point bar sorting (Phi) | 1.16 | 0.23 | 1.12 | 0.91 (Cecil) | 1.63 (Mill (upper)) |

**Table 16.** Summary statistics for reach substrate variables--Continued

| Variable | Mean | Standard deviation | Median | Minimum | Maximum |
|---|---|---|---|---|---|
| **Current River System, n = 17 except point bars where n = 15** | | | | | |
| Bedrock in thalweg (percent) | 2 | 5 | 0 | 0 (many) | 19 (Rocky) |
| Mud and sand in thalweg (percent) | 8 | 12 | 5 | 0 (many) | 46 (Gladden) |
| Gravel in thalweg (percent) | 67 | 20 | 67 | 33 (Jacks Fork) | 94 (Carter) |
| Cobbles and boulders in thalweg (percent) | 22 | 20 | 14 | 2 (Gladden) | 66 (Jacks Fork) |
| Thalweg embeddedness index | 0.177 | 0.123 | 0.163 | 0.013 (Carr) | 0.502 (Gladden) |
| Glide embeddedness (percent) | 20 | 19 | 15 | 1 (Jacks Fork, Sinking) | 82 (Gladden) |
| Glide D16 (mm) | 9 | 4 | 9 | 4 (Gladden) | 18 (Jacks Fork) |
| Glide D50 (mm) | 20 | 7 | 19 | 7 (Gladden) | 32 (Jacks Fork) |
| Glide D84 (mm) | 48 | 23 | 44 | 25 (Gladden) | 120 (Rocky) |
| Glide sorting (Phi) | 1.26 | 0.29 | 1.15 | 0.89 (Gladden) | 2.18 (Rocky) |
| Point bar D16 (mm) | 10 | 4 | 8 | 5 (Carter, Gladden, Mill) | 19 (Spring Valley) |
| Point bar D50 (mm) | 24 | 11 | 21 | 10 (Mill) | 49 (Jacks Fork) |
| Point bar D84 (mm) | 49 | 20 | 45 | 15 (Mill) | 99 (Jacks Fork) |
| Point bar sorting (Phi) | 1.11 | 0.16 | 1.11 | 0.76 (Mill) | 1.37 (Carter) |

glide particle-size models also included two different variables: an indicator variable to specify river system (Buffalo or Current) and drainage-basin shape. These variables suggest that glides in the Buffalo have coarser substrates and that longer, narrower drainage basins have smaller particle sizes. The signficance of the river-system indicator variable supports the association between particle size and relief elements – particle sizes are larger in the more rugged Buffalo River system. The relation with basin shape is more puzzling. It may be indicative of downstream fining in longer stream networks or it may be influenced by the high proportion of karst in the long, narrow drainage basins of the west Current. It also may be a spurious correlation.

### Buffalo River System

The substrate multiple regression models are generally stronger and more consistent for the Buffalo River subset than for the combined set of drainage basins. Models again show a relation between thalweg and glide particle size and relief elements, geology, and cleared land area (table 20). One of the strongest relations ($R^2 = 0.85$) is for the proportion of gravel along the thalweg (fig. 34). An increase in gravel is associated with a decrease in the proportion of streamside bluffs, an increase in carbonate bedrock area (fig. 34A), and an increase in the proportion of cleared land in the drainage basin or in the stream buffer (fig. 34B). This is one of the most convincing models to show a relation between land use and stream conditions. After accounting for known physiographic and geologic differences, a relation with land use persists. The proportion of gravel in the streams appears to increase with the proportion of cleared land. Visual observations also supported this hypothesis – in some Buffalo streams, cobbles appeared to be embedded in a matrix of chert gravel (fig. 32D), as though a recent influx of gravel had inundated the stream.

Many of the other substrate measures show relations with relief elements, land use, or geology but models are not significant when all three variable categories are represented (table 20). For example, after accounting for differences in the proportion of stream-side bluffs, an increase in the 84th percentile of glide particle size was negatively associated with carbonate bedrock area or with one of four land-use variables. However, the model is not significant when all three variables are in the model. As in many of the Buffalo channel-geometry regression models, the land use and

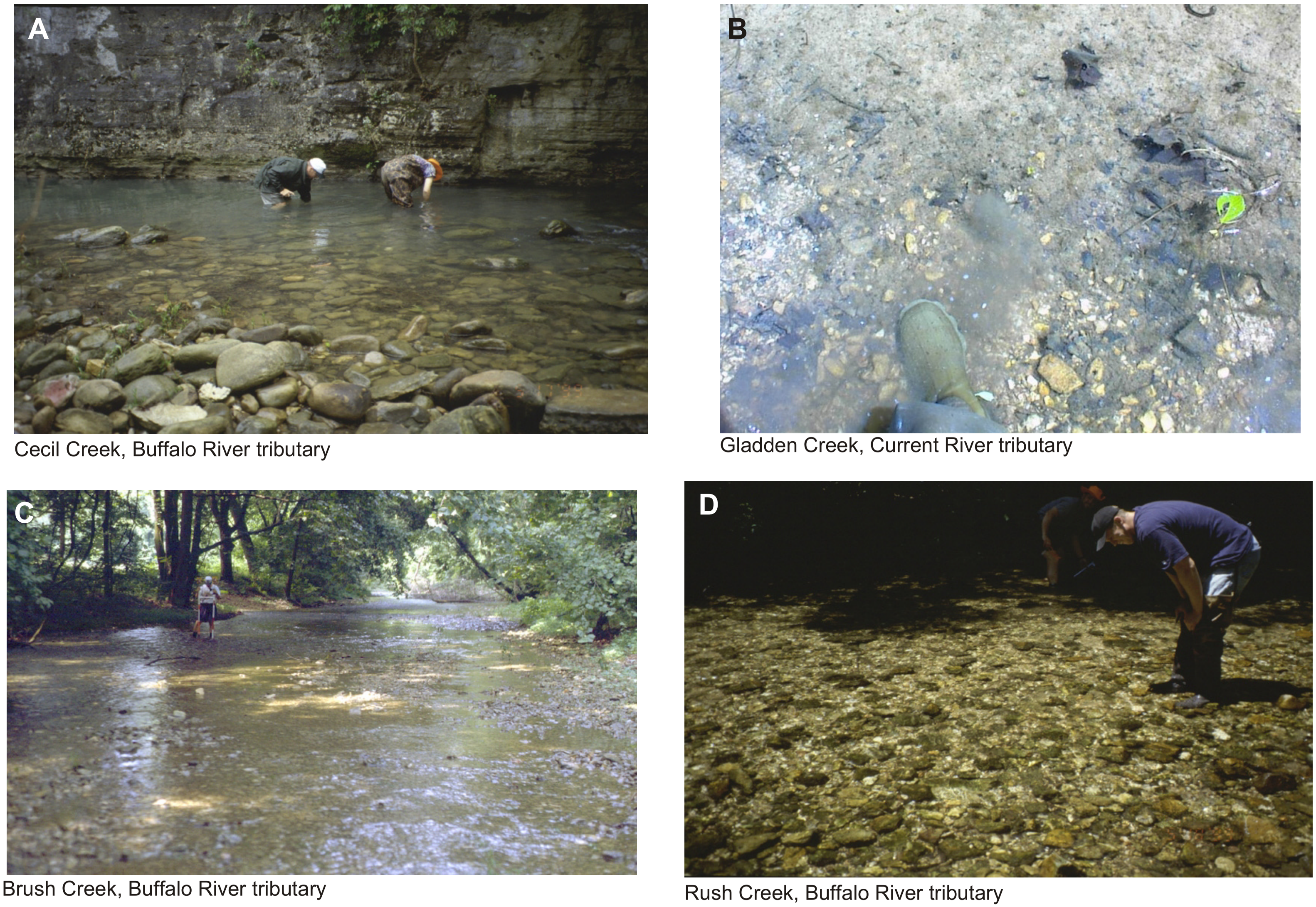



**Figure 32.** Photographs showing the range of substrate types within the study tributary reaches. A. Cecil Creek and many tributaries draining the Boston Mountains have cobble-dominated substrate. B. Gladden Creek has the finest substrate of any tributary in the study, with sand covering much of the channel. C. Brush Creek has a gravel-dominated substrate as do many streams in the Current and lower Buffalo River system. Brush Creek also has an unusually flat longitudinal profile with extended, gravel-dominated riffles. D. Rush Creek has a mixture of cobble and gravel substrate and is an example of a stream where gravel appears to surround and embed cobbles.

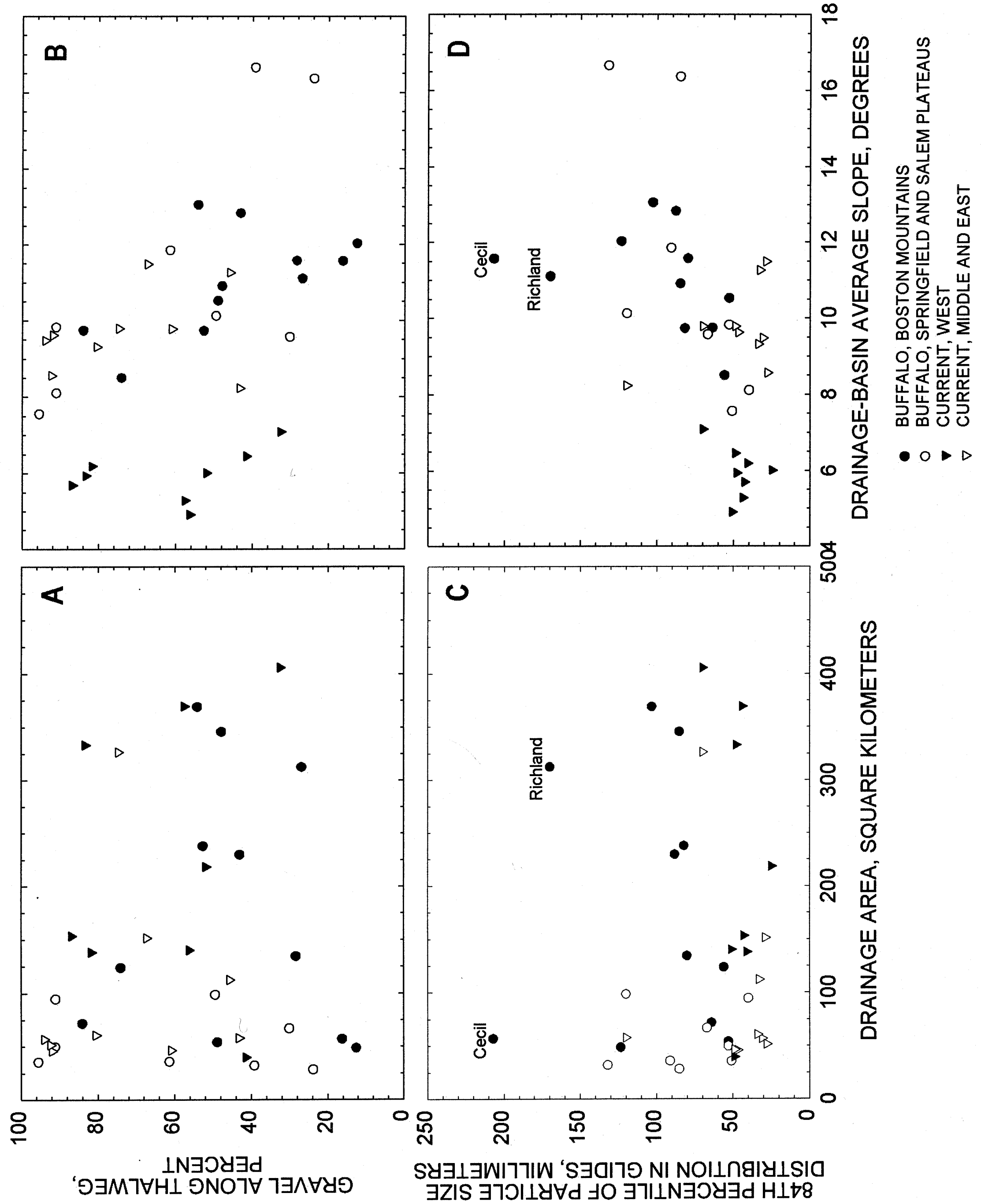



**Figure 33.** Example scatter plots showing relations among channel-substrate variables, drainage area, and drainage-basin average slope.

**Table 17.** Spearman rank correlation coefficients for relations between reach-substrate variables

[shaded values significant at p ≤ 0.05; bold values > 0.5 or < -0.5; refer to Table 5 for variable definitions]

| Variable | Bedrock in thalweg | Mud and sand in thalweg | Gravel in thalweg | Cobbles and boulders in thalweg | Thalweg embeddedness | Glide embeddedness | Glide D16 | Glide D50 | Glide D84 | Glide sorting | Point bar D16 | Point bar D50 | Point bar D84 | Point bar sorting |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Both River Systems, n = 36, except point bars where n = 27** | | | | | | | | | | | | | | |
| Bedrock in thalweg | **1.00** | | | | | | | | | | | | | |
| Mud and sand in thalweg | -0.24 | **1.00** | | | | | | | | | | | | |
| Gravel in thalweg | **-0.63** | 0.09 | **1.00** | | | | | | | | | | | |
| Cobbles and boulders in thalweg | 0.30 | -0.36 | **-0.76** | **1.00** | | | | | | | | | | |
| Thalweg embeddedness | -0.22 | **0.61** | 0.05 | -0.16 | **1.00** | | | | | | | | | |
| Glide embeddedness | -0.03 | **0.64** | -0.16 | -0.06 | **0.67** | **1.00** | | | | | | | | |
| Glide D16 | 0.22 | -0.44 | -0.01 | 0.21 | -0.49 | **-0.68** | **1.00** | | | | | | | |
| Glide D50 | 0.43 | -0.41 | -0.45 | **0.58** | -0.38 | -0.41 | **0.66** | **1.00** | | | | | | |
| Glide D84 | **0.59** | -0.44 | **-0.64** | **0.69** | -0.35 | -0.29 | 0.45 | **0.90** | **1.00** | | | | | |
| Glide sorting | 0.28 | 0.16 | -0.50 | 0.46 | 0.27 | **0.52** | -0.33 | 0.14 | 0.38 | **1.00** | | | | |
| Point bar D16 | 0.25 | -0.38 | -0.07 | 0.40 | -0.46 | **-0.50** | **0.66** | **0.67** | **0.65** | -0.01 | **1.00** | | | |
| Point bar D50 | 0.33 | -0.48 | -0.12 | 0.36 | **-0.59** | -0.49 | **0.65** | **0.70** | **0.70** | 0.05 | **0.86** | **1.00** | | |
| Point bar D84 | 0.22 | -0.48 | -0.19 | 0.42 | **-0.61** | -0.44 | **0.57** | **0.57** | **0.54** | -0.05 | **0.65** | **0.85** | **1.00** | |
| Point bar sorting | -0.20 | -0.21 | 0.17 | -0.15 | -0.17 | -0.03 | -0.16 | -0.15 | -0.21 | -0.13 | -0.39 | -0.08 | 0.25 | **1.00** |
| **Buffalo River System, n = 19 except point bars where n = 12** | | | | | | | | | | | | | | |
| Bedrock in thalweg | **1.00** | | | | | | | | | | | | | |
| Mud and sand in thalweg | 0.10 | **1.00** | | | | | | | | | | | | |
| Gravel in thalweg | **-0.65** | -0.19 | **1.00** | | | | | | | | | | | |
| Cobbles and boulders in thalweg | 0.08 | -0.05 | **-0.68** | **1.00** | | | | | | | | | | |
| Thalweg embeddedness | 0.07 | 0.37 | -0.34 | 0.48 | **1.00** | | | | | | | | | |
| Glide embeddedness | 0.40 | 0.47 | **-0.62** | **0.56** | **0.58** | **1.00** | | | | | | | | |
| Glide D16 | -0.24 | -0.17 | 0.33 | -0.07 | 0.01 | -0.50 | **1.00** | | | | | | | |
| Glide D50 | -0.29 | 0.18 | -0.28 | **0.74** | 0.38 | 0.21 | 0.37 | **1.00** | | | | | | |
| Glide D84 | 0.18 | 0.08 | **-0.68** | **0.88** | 0.31 | 0.42 | 0.05 | **0.80** | **1.00** | | | | | |
| Glide sorting | 0.22 | 0.34 | -0.50 | **0.53** | 0.40 | **0.74** | -0.30 | 0.33 | **0.52** | **1.00** | | | | |
| Point bar D16 | -0.27 | 0.28 | 0.13 | 0.21 | 0.01 | 0.10 | 0.47 | **0.52** | 0.37 | 0.00 | **1.00** | | | |
| Point bar D50 | 0.01 | 0.28 | -0.09 | 0.26 | -0.22 | 0.03 | 0.42 | **0.60** | 0.48 | 0.31 | **0.64** | **1.00** | | |
| Point bar D84 | -0.02 | 0.49 | -0.09 | 0.06 | -0.24 | 0.11 | 0.11 | 0.20 | 0.14 | 0.25 | 0.38 | **0.77** | **1.00** | |
| Point bar sorting | -0.16 | -0.33 | 0.11 | -0.19 | -0.45 | -0.20 | **-0.50** | -0.41 | -0.42 | -0.11 | **-0.64** | -0.23 | 0.17 | **1.00** |

**Table 17.** Spearman rank correlation coefficients for relations between reach-substrate variables--Continued

| Variable | Bedrock in thalweg | Mud and sand in thalweg | Gravel in thalweg | Cobbles and boulders in thalweg | Thalweg embeddedness | Glide embeddedness | Glide D16 | Glide D50 | Glide D84 | Glide sorting | Point bar D16 | Point bar D50 | Point bar D84 | Point bar sorting |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Current River System, n = 17, except point bars where n = 15** | | | | | | | | | | | | | | |
| Bedrock in thalweg | **1.00** | | | | | | | | | | | | | |
| Mud and sand in thalweg | -0.24 | **1.00** | | | | | | | | | | | | |
| Gravel in thalweg | **-0.60** | 0.04 | **1.00** | | | | | | | | | | | |
| Cobbles and boulders in thalweg | 0.43 | **-0.53** | **-0.69** | **1.00** | | | | | | | | | | |
| Thalweg embeddedness | -0.10 | **0.64** | 0.09 | **-0.55** | **1.00** | | | | | | | | | |
| Glide embeddedness | -0.28 | **0.69** | 0.14 | **-0.56** | **0.77** | **1.00** | | | | | | | | |
| Glide D16 | 0.19 | -0.34 | 0.02 | 0.36 | **-0.69** | **-0.69** | **1.00** | | | | | | | |
| Glide D50 | **0.53** | -0.38 | -0.28 | **0.55** | **-0.52** | **-0.82** | **0.73** | **1.00** | | | | | | |
| Glide D84 | **0.69** | -0.44 | -0.43 | **0.65** | **-0.56** | **-0.74** | **0.54** | **0.87** | **1.00** | | | | | |
| Glide sorting | 0.46 | -0.05 | -0.37 | 0.34 | 0.05 | 0.11 | -0.38 | 0.04 | 0.42 | **1.00** | | | | |
| Point bar D16 | 0.28 | -0.30 | -0.12 | **0.52** | **-0.52** | **-0.64** | **0.61** | **0.69** | **0.75** | 0.11 | **1.00** | | | |
| Point bar D50 | 0.21 | -0.27 | 0.00 | 0.35 | -0.47 | **-0.54** | 0.50 | **0.59** | **0.61** | 0.08 | **0.94** | **1.00** | | |
| Point bar D84 | 0.08 | **-0.53** | -0.08 | 0.49 | **-0.58** | **-0.57** | 0.48 | 0.45 | 0.43 | -0.14 | **0.75** | **0.81** | **1.00** | |
| Point bar sorting | 0.02 | -0.24 | 0.26 | -0.12 | 0.14 | 0.22 | -0.10 | -0.17 | -0.31 | -0.09 | -0.24 | -0.05 | 0.27 | **1.00** |

carbonate variables appear to act as proxy variables for each other. When one is in the model, the others are not significant.

A similar series of models also are significant for the proportion of cobbles and boulders along the thalweg and for the degree of sorting in glides (table 20). Cobbles and boulders are more abundant along the thalweg and glide substrates are poorly sorted in drainage basins with rugged relief and low proportions of carbonate and cleared land. Again, these models are not significant when all three categories of explanatory variables are represented. However, the relation with glide sorting may be another indication of the role of carbonate in sediment supply to streams. The primary byproducts of carbonate weathering are clay and gravelly chert residuum – particle sizes within a narrower range than those produced by sandstone weathering. The positive association between carbonate bedrock and better-sorted bed-load sediments suggest another way that bedrock may influence habitat characteristics.

One relation with fine substrate is also significant for the Buffalo subset (table 20). Thalweg embeddedness is negatively associated with carbonate bedrock area and positively associated with steep cleared land area. The relation with geology suggests that drainage basins with less carbonate have more embeddedness – this hypothesis is consistent with the presence of more sandstone in these drainage basins. Weathering sandstone provides an abundant source of sand-sized sediment that is lacking in the carbonate dominated drainage basins. The relation with steep, cleared land area is also consistent with a second hypothesis; that cleared land increases sediment supply and embeddedness (table 1). The weakness of this model is that it does not include a relief variable. The basin-scale analyses showed that steep, cleared land is strongly negatively correlated with drainage-basin average slope (table 8). It is possible that embeddedness is related to physiographic differences and not to land use patterns.

The many regression models and proxy variables are indicative of the numerous correlations among basin-scale variables

**Table 18.** Spearman rank correlation coefficients for relations between reach-substrate variables and drainage-basin variables
[shaded values significant at p ≤ 0.05; bold values > 0.5 or < -0.5; refer to Table 5 for variable definitions]

| Variable | Carbonate bedrock area | Drainage area | Drainage basin shape | Elevation range | Drainage basin average slope | Bluff area in stream buffer | Cleared land area | Steep, cleared land area | Cleared land in stream buffer | Road density | Road density in stream buffer |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Both River Systems, n = 36 except point bars where n = 27** | | | | | | | | | | | |
| Bedrock in thalweg | -0.36 | -0.03 | -0.37 | 0.49 | 0.38 | **0.54** | 0.06 | 0.28 | -0.14 | -0.21 | -0.29 |
| Mud and sand in thalweg | -0.01 | 0.13 | 0.22 | -0.32 | -0.29 | -0.20 | -0.01 | -0.35 | -0.03 | 0.07 | 0.01 |
| Gravel in thalweg | **0.52** | -0.06 | 0.25 | -0.43 | -0.48 | **-0.70** | 0.26 | 0.13 | 0.45 | 0.40 | 0.34 |
| Cobbles and boulders in thalweg | -0.38 | 0.04 | -0.17 | 0.44 | **0.52** | **0.60** | -0.36 | -0.11 | -0.49 | -0.38 | -0.12 |
| Thalweg embeddedness | -0.12 | 0.42 | 0.20 | -0.20 | -0.31 | -0.07 | 0.07 | -0.26 | 0.28 | 0.01 | 0.05 |
| Glide embeddedness | -0.15 | 0.12 | 0.20 | -0.15 | -0.04 | 0.00 | -0.13 | -0.38 | 0.06 | 0.07 | 0.21 |
| Glide D16 | -0.14 | 0.07 | -0.33 | 0.35 | 0.22 | 0.24 | 0.21 | **0.54** | 0.02 | -0.12 | -0.21 |
| Glide D50 | -0.42 | -0.01 | -0.32 | **0.71** | **0.57** | **0.50** | -0.04 | 0.37 | -0.30 | -0.35 | -0.20 |
| Glide D84 | -0.43 | -0.04 | -0.33 | **0.68** | **0.60** | **0.61** | -0.18 | 0.19 | -0.42 | -0.37 | -0.23 |
| Glide sorting | -0.22 | 0.11 | 0.00 | 0.18 | 0.22 | 0.33 | -0.23 | -0.28 | -0.27 | 0.01 | 0.09 |
| Point bar D16 | 0.10 | -0.07 | -0.26 | 0.50 | 0.32 | 0.15 | -0.12 | 0.25 | -0.33 | -0.25 | -0.12 |
| Point bar D50 | 0.11 | -0.26 | -0.35 | 0.47 | 0.46 | 0.20 | -0.13 | 0.35 | -0.44 | -0.12 | -0.02 |
| Point bar D84 | 0.23 | -0.30 | -0.36 | 0.40 | **0.53** | 0.21 | -0.25 | 0.27 | **-0.50** | -0.29 | 0.08 |
| Point bar sorting | 0.09 | -0.24 | -0.05 | -0.27 | 0.06 | -0.08 | 0.01 | 0.08 | 0.09 | -0.03 | 0.27 |
| **Buffalo River System, n = 19 except point bars where n = 12** | | | | | | | | | | | |
| Bedrock in thalweg | -0.22 | -0.08 | -0.47 | -0.07 | 0.36 | **0.52** | -0.35 | -0.22 | -0.25 | -0.15 | -0.31 |
| Mud and sand in thalweg | -0.08 | -0.28 | **-0.58** | -0.01 | -0.02 | -0.20 | -0.12 | -0.06 | -0.17 | -0.23 | 0.12 |
| Gravel in thalweg | **0.66** | 0.03 | 0.47 | -0.21 | **-0.62** | **-0.62** | **0.73** | **0.69** | **0.55** | **0.53** | 0.38 |
| Cobbles and boulders in thalweg | **-0.68** | 0.25 | -0.09 | 0.47 | **0.66** | **0.57** | **-0.67** | **-0.65** | -0.44 | -0.42 | -0.07 |
| Thalweg embeddedness | **-0.76** | **0.54** | -0.21 | **0.63** | 0.00 | 0.24 | -0.08 | -0.19 | 0.22 | -0.32 | -0.02 |
| Glide embeddedness | **-0.51** | 0.18 | -0.28 | 0.43 | 0.37 | 0.28 | -0.44 | -0.45 | -0.22 | -0.28 | 0.09 |
| Glide D16 | 0.17 | 0.05 | -0.03 | -0.02 | -0.08 | 0.16 | 0.25 | 0.27 | 0.23 | 0.19 | 0.08 |
| Glide D50 | -0.41 | 0.10 | -0.07 | 0.28 | 0.47 | 0.36 | -0.45 | -0.39 | -0.32 | -0.32 | 0.06 |
| Glide D84 | **-0.53** | 0.10 | -0.21 | 0.25 | **0.72** | **0.68** | **-0.74** | **-0.57** | **-0.62** | -0.43 | -0.17 |
| Glide sorting | -0.35 | 0.34 | -0.25 | 0.35 | 0.40 | 0.49 | -0.44 | -0.38 | -0.30 | -0.01 | 0.15 |
| Point bar D16 | 0.10 | -0.24 | -0.02 | 0.26 | 0.30 | -0.01 | -0.36 | -0.14 | -0.35 | -0.29 | 0.03 |
| Point bar D50 | 0.21 | **-0.52** | -0.19 | -0.20 | 0.48 | 0.02 | -0.48 | -0.25 | **-0.82** | -0.01 | -0.01 |
| Point bar D84 | 0.20 | **-0.74** | -0.32 | -0.28 | 0.22 | -0.31 | -0.36 | -0.34 | **-0.86** | -0.06 | 0.00 |
| Point bar sorting | 0.14 | -0.28 | 0.26 | **-0.55** | -0.18 | -0.41 | 0.14 | -0.02 | -0.14 | 0.28 | 0.17 |

**Table 18.** Spearman rank correlation coefficients for relations between reach-substrate variables and drainage-basin variables--Continued

| Variable | Carbonate bedrock area | Drainage area | Drainage basin shape | Elevation range | Drainage basin average slope | Bluff area in stream buffer | Cleared land area | Steep, cleared land area | Cleared land in stream buffer | Road density | Road density in stream buffer |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Current River System, n = 17 except point bars where n = 15** | | | | | | | | | | | |
| Bedrock in thalweg | -0.37 | 0.21 | -0.16 | 0.16 | -0.35 | 0.28 | 0.36 | 0.21 | 0.13 | -0.29 | -0.29 |
| Mud and sand in thalweg | -0.25 | 0.39 | **0.62** | -0.01 | -0.36 | 0.07 | 0.29 | -0.04 | 0.01 | 0.30 | -0.31 |
| Gravel in thalweg | 0.12 | -0.20 | -0.19 | -0.30 | 0.10 | **-0.55** | -0.11 | 0.00 | 0.22 | 0.18 | 0.30 |
| Cobbles and boulders in thalweg | 0.19 | -0.10 | -0.12 | 0.29 | 0.26 | 0.42 | -0.32 | -0.14 | -0.48 | -0.32 | -0.02 |
| Thalweg embeddedness | -0.07 | 0.24 | 0.33 | -0.05 | -0.30 | 0.02 | 0.39 | 0.25 | 0.37 | 0.21 | 0.00 |
| Glide embeddedness | -0.06 | 0.05 | **0.61** | -0.16 | -0.13 | -0.05 | 0.22 | 0.11 | 0.29 | 0.39 | 0.26 |
| Glide D16 | -0.19 | 0.26 | -0.46 | -0.12 | -0.05 | 0.00 | 0.03 | 0.17 | -0.07 | -0.27 | -0.34 |
| Glide D50 | -0.15 | 0.22 | -0.44 | 0.15 | -0.10 | 0.22 | 0.04 | 0.10 | -0.19 | -0.36 | -0.44 |
| Glide D84 | -0.12 | 0.10 | -0.32 | 0.26 | -0.16 | 0.12 | 0.02 | -0.08 | -0.21 | -0.32 | -0.33 |
| Glide sorting | 0.01 | -0.34 | 0.21 | 0.15 | -0.08 | 0.02 | -0.06 | -0.24 | -0.19 | 0.10 | 0.09 |
| Point bar D16 | 0.33 | 0.21 | -0.25 | 0.42 | 0.11 | 0.12 | -0.18 | -0.18 | -0.25 | -0.30 | -0.12 |
| Point bar D50 | 0.31 | 0.14 | -0.24 | 0.35 | 0.21 | 0.21 | -0.23 | -0.19 | -0.25 | -0.28 | 0.02 |
| Point bar D84 | 0.44 | 0.09 | -0.26 | 0.37 | **0.52** | 0.31 | -0.46 | -0.24 | -0.31 | **-0.58** | 0.26 |
| Point bar sorting | 0.02 | -0.20 | -0.05 | -0.27 | 0.38 | 0.28 | -0.10 | 0.22 | 0.21 | -0.30 | 0.47 |

in the Buffalo. Drainage basins with more carbonate also tend to have less relief and more cleared land. Since these variables are correlated, it is difficult to separate out relations with one variable from the others. Instead, what is most clear is that the drainage basins with these three characteristics together tend to have streams with the following substrate characteristics: a greater proportion of gravel than cobbles and boulders along the thalweg, finer substrates in glides and on point bars, well sorted glide substrates, and little embeddedness.

It is also interesting that we found a strong association between the 84th percentile from point bar particle size measurements and drainage area. This sample included only the drainage basins with more than 30 percent carbonate bedrock area (n = 9) since substrate in other drainage basins was too large to be appropriate for the photosieve technique. While for all other substrate measures, there was no apparent relation with drainage area, the relation was strong for the point bar subset. This suggests that relations with drainage area often are masked by the major differences in physiography in the Buffalo River system. When drainage basins are subset, the relation with drainage area became apparent. This is another example of how more subtle impacts may be identified when streams are subset into physiographically similar groups.

## Current River System

We did not find any significant multiple regression models for reach substrate in the Current River tributaries. As suggested earlier, many hypotheses may explain the lack of relations including: differences between the Current groups, local geologic differences such as the presence of igneous rocks in the middle Current basins, and the prevalence of karst drainage networks.

To investigate differences in substrate between the Current groups, we calculated correlation coefficients separately for each group (table 21). In these correlations, we introduced a new explanatory variable, the proportion of Gasconade

**Table 19.** Selected multiple regression models for reach-substrate variables and all study drainage basins; explanatory variables signficant at $p \leq 0.05$; n = 36 unless specified

[m, meters; $m^2$, square meters]

| | | Model coefficients for explanatory variables | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Geology | Physiography | | | | Land use | | | |
| Response variable | Intercept | Indicator for river system[1] | Carbonate bedrock, as a proportion | Drainage basin shape | Elevation range, in m | Drainage basin average slope, in degrees | Bluff area in stream buffer, as a proportion[2] | Cleared land area, as a proportion | Cleared land in stream buffer, as a proportion | Road density, in $m/m^2$ | R squared |
| Gravel in thalweg, as a proportion | 0.6866 | | 0.4396 | | | -0.0345 | | | | | 0.44 |
| | 0.6000 | | 0.3020 | | | | -2.4392 | | | | 0.54 |
| | 0.4631 | | 0.3200 | | | | -2.0043 | | 0.5260 | | 0.60 |
| Cobbles and boulders in thalweg, as a proportion | 0.1807 | | -0.3065 | | | 0.0267 | | | | | 0.32 |
| | 0.4413 | | | | | | 1.8807 | | | -306.718 | 0.40 |
| | 0.2456 | | | | | | 1.7295 | | -0.5067 | | 0.39 |
| | 0.4057 | | -0.2292 | | | | 1.2825 | | -0.5438 | | 0.47 |
| | 0.3662 | | -0.2726 | | 0.0005 | | | -0.7306 | | | 0.51[3] |
| | 0.3887 | | -0.2454 | | | | 1.4645 | -0.5446 | | | 0.46 |
| Glide D84,[4] in mm | 3.3514 | | | | 0.0017 | | 3.8098 | | | | 0.47 |
| | 4.0538 | -0.4561 | | | | | 4.0687 | | | | 0.53 |
| | 3.6913 | | -0.8308 | | | 0.0909 | | | | | 0.47 |
| | 4.0834 | | -0.5734 | | | | 4.9040 | | | | 0.46 |
| | 3.6782 | | | | 0.0026 | | | | -1.6553 | | 0.53 |
| | 4.2853 | -0.4337 | | | | | 3.3613 | | -1.0458 | | 0.59 |
| | 4.5420 | | | | | | 5.3255 | | | -812.095 | 0.48 |
| | 4.0485 | | | -0.0638 | 0.0024 | | | | -1.5594 | | 0.59 |
| | 4.1894 | | | 0.0894 | | | 5.8797 | | | | 0.51 |
| | 4.0358 | | | -0.0705 | 0.0016 | | 2.9259 | | -1.2069 | | 0.64 |

[1] Indicator variable specifies river system, Buffalo = 0 or Current = 1.
[2] Variable was transformed, squareroot(x).
[3] Model excluded Jacks Fork.
[4] Variables were transformed, ln(x).

**Table 20.** Selected multiple regression models for reach-substrate variables and Buffalo River tributaries; explanatory variables signficant at $p \leq 0.05$ and n = 19 unless specified

[m, meters; $m^2$, square meters]

| | | Model coefficients for explanatory variables | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Geology | Physiography | | | | Land use | | | | |
| Response variable | Intercept | Carbonate bedrock area, as a proportion | Drainage area,[1] in $m^2$ | Elevation range, in m | Drainage basin average slope, in degrees | Bluff area in stream buffer, as a proportion[2] | Cleared land area, as a proportion | Steep, cleared land area, as a proportion | Cleared land in stream buffer, as a proportion | Road density, in $m/m^2$ | R squared |
| Gravel in thalweg, as a proportion | 0.7668 | 0.5556 | | | -0.0446 | | | | | | 0.64 |
| | 0.5057 | 0.5366 | | | | -2.7221 | | | | | 0.76[3] |
| | 0.1146 | 0.4369 | | | | | 1.1958 | | | | 0.67 |
| | 0.6013 | | | | | -2.5239 | | 0.9117 | | | 0.57 |
| | 0.3214 | | | | | -2.7120 | | | | 470.052 | 0.63 |
| | 0.5132 | | | | | -2.0252 | | 2.9295 | | | 0.62 |
| | 0.3538 | 0.4069 | | | | -2.0813 | 0.8704 | | | | 0.85[3] |
| | 0.3233 | 0.4741 | | | | -1.6006 | | | 0.8228 | | 0.75 |
| Cobbles and boulders in thalweg, as a proportion | -0.1505 | -0.3975 | | | 0.0611 | | | | | | 0.68[4] |
| | 0.6231 | -0.4103 | | | | | -0.7139 | | | | 0.62 |
| | 0.2296 | | | 0.0007 | | | -1.0724 | | | | 0.55 |
| | 0.0099 | | | 0.0013 | | | | | -1.0058 | | 0.54 |
| | 0.2927 | | | 0.0010 | | | | | | -383.829 | 0.47 |
| | 0.4264 | | | | | 1.9569 | | | | -305.340 | 0.48 |
| Thalweg embeddedness index | 0.1269 | -0.2220 | | | | | | 0.6878 | | | 0.59 |
| Glide D84,[1] in mm | 3.9390 | -0.7127 | | | 0.0721 | | | | | | 0.46 |
| | 5.0638 | -0.7795 | | | | | | | -1.8477 | | 0.56 |
| | 4.4426 | | | | | 3.3184 | -1.8473 | | | | 0.60 |
| | 4.2951 | | | | | 3.9698 | | -3.6492 | | | 0.56 |
| | 4.2989 | | | | | 4.3270 | | | -1.6974 | | 0.64 |
| | 4.6160 | | | | | 4.7828 | | | | -668.573 | 0.60 |
| Glide sorting, in Phi | 1.8375 | -0.7015 | | | | | | | -1.3783 | | 0.45 |
| | 0.9095 | | | 0.0020 | | | | | -2.1003 | | 0.49 |
| Point bar D84,[1] mm | 7.1365 | | -0.1529 | | | | | -1.1653 | | | 0.94[5] |

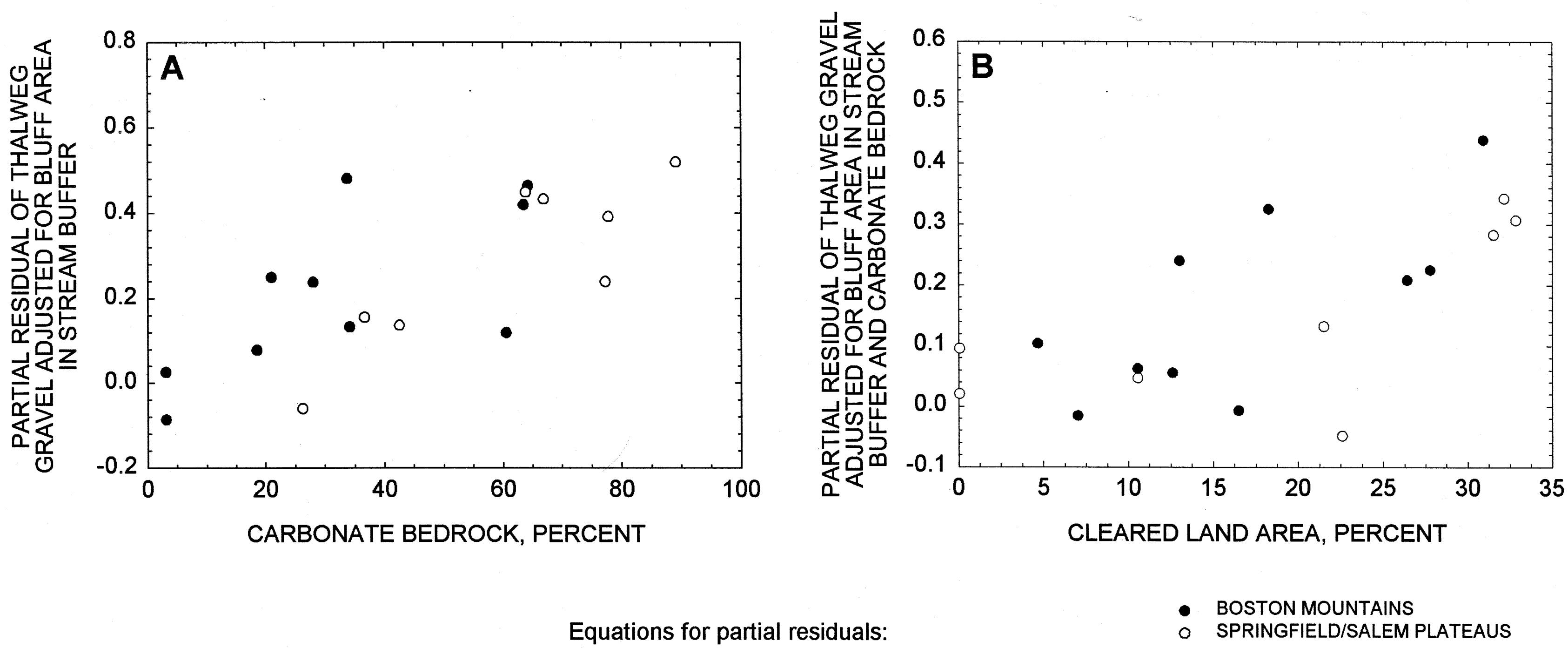
[1] Variables were transformed, ln(x).

[2] Variable was transformed, squareroot(x).

[3] Little Buffalo excluded.

[4] Middle and Leatherwood excluded.

[5] Models included basins with >30% carbonate, n = 9.




Equations for partial residuals:

$$y_{pr\_A} = y_1 - 0.5057 - (-2.7221 * sqrt(x_1))$$
$$y_{pr\_B} = y_1 - 3.3538 - (-2.0813 * sqrt(x_1)) - (0.4069*x_2)$$

where:

$y_{pr\_A}$ = partial residual of gravel along thalweg adjusted for bluff area in stream buffer
$y_1$ =gravel along thalweg, as a proportion
$y_{pr\_B}$ = partial residual of gravel along thalweg adjusted for bluff area in stream buffer and carbonate bedrock area
$x_1$ = bluff area in stream buffer, as a proportion
$x_2$ = carbonate bedrock area in drainage basin, as a proportion

**Figure 34.** Partial residual plots showing relations in the Buffalo river system among gravel along the thalweg, carbonate bedrock, and cleared land area after accounting for differences in bluff area in stream buffers. The partial residuals were derived from the regression models shown in Table 20 using the method outlined in Ramsey and Schafer (1996). Note that Little Buffalo River, with an unusually high bluff area in stream buffers, was excluded from these models.

**Table 21.** Spearman rank correlation coefficients for relations between reach variables and drainage-basin variables, Middle/east and west Current tributary groups

[shaded values significant at $p \leq 0.05$; bold values > 0.5 or < -0.5; refer to Table 5 for variable definitions]

| Variable | Carbonate bedrock area | Gasconade bedrock area | Drainage area | Drainage basin shape | Elevation range | Drainage basin average slope | Bluff area in stream buffer | Cleared land area | Steep, cleared land area | Cleared land in stream buffer | Road density | Road density in stream buffer |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **West Current, n = 8, except point bars where n = 7** | | | | | | | | | | | | |
| Carbonate bedrock area | **1.00** | | | | | | | | | | | |
| Gasconade bedrock area | -0.05 | **1.00** | | | | | | | | | | |
| Drainage area | **0.86** | -0.17 | **1.00** | | | | | | | | | |
| Drainage basin shape | 0.07 | **0.74** | 0.14 | **1.00** | | | | | | | | |
| Elevation range | **0.83** | 0.17 | **0.88** | 0.24 | **1.00** | | | | | | | |
| Drainage basin average slope | 0.36 | -0.02 | -0.02 | -0.26 | 0.12 | **1.00** | | | | | | |
| Bluff area in stream buffer | 0.34 | 0.11 | 0.04 | 0.08 | 0.27 | **0.60** | **1.00** | | | | | |
| Cleared land area | 0.05 | 0.38 | 0.21 | **0.76** | 0.05 | -0.43 | -0.23 | **1.00** | | | | |
| Steep, cleared land area | 0.19 | -0.43 | 0.26 | 0.10 | -0.10 | 0.21 | 0.00 | 0.43 | **1.00** | | | |
| Cleared land area in stream buffer | 0.19 | 0.36 | 0.40 | **0.71** | 0.26 | -0.21 | -0.29 | **0.88** | **0.52** | **1.00** | | |
| Road density | 0.33 | 0.10 | 0.14 | 0.45 | -0.02 | 0.38 | 0.23 | 0.48 | **0.74** | 0.50 | **1.00** | |
| Road density in stream buffer | 0.31 | -0.33 | **0.55** | 0.02 | 0.38 | 0.02 | -0.28 | -0.07 | 0.40 | 0.29 | 0.21 | **1.00** |
| Bedrock in thalweg | -0.22 | 0.05 | 0.05 | 0.12 | 0.20 | 0.10 | 0.16 | -0.07 | 0.07 | 0.20 | -0.24 | 0.32 |
| Mud and sand in thalweg | -0.02 | **0.63** | 0.06 | **0.71** | 0.07 | -0.44 | **-0.50** | **0.56** | -0.12 | **0.56** | 0.26 | 0.18 |
| Gravel in thalweg | -0.10 | 0.00 | -0.10 | 0.05 | -0.10 | **-0.55** | -0.16 | -0.14 | -0.48 | -0.40 | -0.21 | -0.05 |
| Cobbles and boulders in thalweg | 0.02 | **-0.60** | 0.14 | **-0.52** | 0.10 | 0.26 | 0.35 | -0.33 | 0.24 | -0.24 | -0.31 | 0.02 |
| Thalweg embeddedness | 0.05 | **0.57** | 0.14 | **0.69** | 0.12 | -0.43 | **-0.52** | **0.57** | -0.05 | **0.60** | 0.31 | 0.26 |
| Glide embeddedness | -0.17 | **0.67** | -0.05 | **0.79** | -0.05 | -0.50 | -0.48 | **0.69** | -0.05 | **0.64** | 0.29 | 0.07 |
| Glide D16 | 0.23 | **-0.77** | 0.23 | **-0.64** | 0.10 | 0.27 | 0.43 | -0.40 | 0.27 | -0.42 | -0.18 | -0.02 |
| Glide D50 | 0.19 | **-0.83** | 0.19 | **-0.64** | 0.00 | 0.24 | 0.37 | -0.36 | 0.36 | -0.40 | -0.10 | 0.00 |
| Glide D84 | 0.00 | **-0.69** | 0.19 | -0.50 | 0.05 | 0.12 | 0.22 | -0.21 | 0.36 | -0.14 | -0.26 | 0.10 |
| Glide sorting | **-0.65** | -0.01 | -0.42 | 0.24 | -0.47 | -0.10 | -0.18 | 0.11 | 0.34 | 0.23 | 0.17 | 0.36 |
| Point bar D16 | 0.41 | **-0.79** | **0.50** | **-0.76** | 0.32 | 0.09 | 0.14 | **-0.74** | 0.00 | **-0.59** | -0.49 | 0.34 |
| Point bar D50 | 0.43 | **-0.64** | 0.36 | **-0.68** | 0.29 | 0.43 | 0.38 | **-0.93** | 0.00 | **-0.75** | -0.18 | 0.43 |
| Point bar D84 | 0.50 | **-0.61** | **0.54** | **-0.61** | 0.46 | 0.29 | 0.33 | **-0.86** | -0.11 | **-0.64** | -0.36 | 0.46 |
| Point bar sorting | -0.22 | 0.07 | -0.09 | 0.43 | 0.09 | 0.07 | **0.50** | -0.04 | 0.24 | 0.04 | 0.28 | 0.45 |

**Table 21.** Spearman rank correlation coefficients for Middle/east and west Current tributary groups--Continued

| Variable | Carbonate bedrock area | Gasconade bedrock area | Drainage area | Drainage basin shape | Elevation range | Drainage basin average slope | Bluff area in stream buffer | Cleared land area | Steep, cleared land area | Cleared land in stream buffer | Road density | Road density in stream buffer |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Middle and East Current, n = 9 except point bars where n = 8** | | | | | | | | | | | | |
| Carbonate bedrock area | **1.00** | | | | | | | | | | | |
| Gasconade bedrock area | 0.07 | **1.00** | | | | | | | | | | |
| Drainage area | -0.03 | **0.57** | **1.00** | | | | | | | | | |
| Drainage basin shape | 0.43 | 0.40 | 0.17 | **1.00** | | | | | | | | |
| Elevation range | 0.33 | -0.17 | 0.25 | **0.53** | **1.00** | | | | | | | |
| Drainage basin average slope | 0.44 | 0.47 | 0.41 | **0.64** | 0.18 | **1.00** | | | | | | |
| Bluff area in stream buffer | 0.23 | 0.15 | **0.64** | **0.57** | **0.55** | **0.59** | **1.00** | | | | | |
| Cleared land area | -0.25 | -0.45 | -0.18 | **-0.85** | -0.42 | **-0.64** | -0.41 | **1.00** | | | | |
| Steep, cleared land area | -0.13 | -0.05 | 0.22 | **-0.72** | -0.47 | -0.35 | -0.23 | **0.87** | **1.00** | | | |
| Cleared land area in stream buffer | -0.18 | -0.32 | -0.32 | **-0.82** | **-0.58** | **-0.50** | **-0.57** | **0.93** | **0.80** | **1.00** | | |
| Road density | 0.25 | 0.22 | **-0.52** | 0.05 | -0.33 | -0.21 | **-0.71** | -0.07 | -0.05 | 0.10 | **1.00** | |
| Road density in stream buffer | -0.05 | 0.33 | -0.38 | 0.02 | **-0.68** | -0.11 | -0.34 | 0.00 | -0.03 | 0.20 | 0.45 | **1.00** |
| Bedrock in thalweg | -0.25 | -0.37 | 0.37 | -0.30 | **0.52** | -0.32 | 0.33 | 0.32 | 0.18 | 0.09 | **-0.73** | **-0.59** |
| Mud and sand in thalweg | 0.28 | 0.40 | 0.21 | **0.77** | 0.26 | **0.58** | 0.35 | **-0.67** | -0.40 | **-0.67** | 0.27 | -0.13 |
| Gravel in thalweg | -0.15 | 0.10 | -0.33 | **-0.60** | **-0.78** | -0.25 | **-0.80** | **0.55** | **0.58** | **0.75** | **0.57** | 0.37 |
| Cobbles and boulders in thalweg | 0.18 | -0.03 | 0.38 | **0.55** | **0.73** | 0.33 | **0.77** | **-0.62** | **-0.62** | **-0.78** | **-0.57** | -0.37 |
| Thalweg embeddedness | 0.22 | -0.15 | 0.13 | 0.02 | -0.10 | -0.12 | 0.37 | 0.28 | 0.40 | 0.08 | -0.10 | 0.12 |
| Glide embeddedness | 0.24 | **0.58** | 0.07 | 0.39 | -0.45 | 0.30 | 0.13 | -0.22 | 0.04 | -0.12 | 0.38 | **0.71** |
| Glide D16 | -0.10 | 0.31 | 0.26 | -0.09 | -0.05 | 0.39 | -0.10 | 0.09 | 0.22 | 0.26 | -0.09 | -0.28 |
| Glide D50 | -0.08 | -0.39 | 0.25 | -0.02 | **0.68** | 0.09 | 0.34 | 0.08 | -0.02 | -0.05 | **-0.59** | **-0.88** |
| Glide D84 | -0.20 | -0.37 | 0.02 | 0.03 | **0.70** | -0.16 | 0.15 | -0.17 | -0.43 | -0.27 | -0.45 | **-0.57** |
| Glide sorting | 0.15 | -0.47 | -0.38 | 0.27 | 0.48 | -0.24 | 0.17 | -0.30 | **-0.63** | -0.40 | -0.13 | 0.03 |
| Point bar D16 | **0.69** | -0.37 | -0.22 | 0.35 | **0.63** | 0.39 | 0.30 | -0.11 | -0.39 | -0.11 | -0.19 | -0.23 |
| Point bar D50 | **0.52** | -0.38 | -0.33 | 0.24 | 0.40 | 0.35 | 0.19 | 0.00 | -0.33 | 0.05 | -0.21 | -0.02 |
| Point bar D84 | 0.05 | 0.00 | 0.10 | 0.17 | 0.21 | **0.61** | 0.43 | -0.14 | -0.33 | -0.12 | **-0.71** | 0.02 |
| Point bar sorting | -0.24 | -0.14 | 0.14 | -0.24 | **-0.62** | 0.23 | 0.20 | 0.24 | 0.33 | 0.26 | -0.48 | 0.17 |

Dolomite within each drainage basin. This variable helped differentiate between the types of carbonate bedrock in the Current River drainage basin.

In the middle and east Current, there are strong correlations are between measurements of coarse substrate and the drainage-basin variables. Both thalweg and glide particle size measurements are correlated with elevation range. Thalweg measurements also are correlated with streamside bluffs and with many of the land-use variables. Particle size is positively associated with elevation range and the prevalence of streamside bluffs. A change from cobble/boulder to gravel substrate also is correlated with an increase in cleared land area both in the drainage basin and the stream buffers and with an increase in road density. This appears to be another case where correlations exist with natural and anthropogenic factors that are correlated themselves. In the middle and east Current, elevation range and bluff area are correlated with many of the land use variables (table 21). Multiple regression models that included both types of explanatory variables were not significant.

In the west Current group, many substrate variables show correlations with the area of Gasconade Dolomite within the drainage basins and with drainage-basin shape. These two variables are correlated and may be indicators of the role of karst hydrology in the stream systems. The Gasconade Dolomite underlies valley bottoms in the west Current (fig. 15). This portion of the formation often contains karst dissolution features. As with other karst horizons in the region, dissolution appears to be concentrated in this zone because it underlies a sandy unit, the Roubidoux Formation (R. Harrison, research geologist, U.S. Geological Survey, Reston, VA, oral communication, July 2000). The correlations with substrate variables suggest another way karst networks may impact streams. Gasconade Dolomite bedrock is positively correlated with mud/sand and embeddedness along the thalweg and in glides, less cobbles/boulders along the thalweg and smaller particle sizes in glides and on point bars. With well developed karst systems, these streams may lack sufficient transport capacity to transport coarse substrate and to maintain sufficient baseflows to keep fine sediment entrained.

It is also interesting that many of the fine substrate variables are also correlated with variables measuring cleared land area among the west Current group. Glide and thalweg embeddedness increased and point bar particle size decreased as cleared land area increased. These correlations suggest an anthropogenic mechanism for fine sediment in the west Current basins. There is however, some correlation between cleared land area and Gasconade Dolomite bedrock area and multiple regression models with both variables are not significant. Therefore, the increase in embeddedness and decrease in particle size is consistent with either natural or anthropogenic impacts on streams (table 1).

## Channel Stability

Nearly all reaches had at least some proportion of eroding banks (table 22) and measures of bank erosion and bank vegetation were correlated (table 23). On average, 43 percent of all banks were moderately or severely eroding and 16 percent of banks were severely eroding with steep cutbanks and protruding roots (fig. 35). Six out of seven of the study reaches with more than 60 percent eroding banks are in the Buffalo drainage basin. Streams with more eroding banks had less bank vegetation as measured by our bank vegetation index (table 23) – the variable we used to integrate bank vegetation cover estimates made at each thalweg survey point. Overall however, bank vegetation scores also tended to be lower in the Current. This difference may be a byproduct of our sampling protocols: we grouped bedrock banks in the same category as banks with 100 percent vegetation cover because both are resistant to erosion. The Current River tributaries may have scored lower in variables of bank vegetation because they have a lower proportion of bluffs and bedrock banks (table 7).

Measures of channel sinuosity and glide canopy cover showed few trends perhaps because sampling scale impacted both measurements. Thalweg sinuosity, for example, was measured over the length of each study reach. In many cases, however, we found that the reach length was too short to capture overall sinuosity of the channel. The thalweg profile may have covered a fairly straight length of stream, when over a larger scale the channel meandered more extensively. An ongoing project with the University of Missouri (M. Urban, Assistant Professor of Geography, University of Missouri-Columbia, oral communication, June 2000) will measure sinuosity for some study tributary sites from 1:9000-scale aerial photography – a scale that is better suited for evaluation of channel metrics such as sinuosity. Our canopy cover estimates also appear to be biased by scale. We measured cover at the water's edge of each glide cross section with a densiometer (table 5). In large channels however, we found that cross-sections became too widely spaced to successfully evaluate canopy cover for the reach. The ongoing University of Missouri study will test the utility of measuring canopy cover from aerial photography.

**Table 22.** Summary statistics for reach-stability variables

[refer to Table 5 for variable definitions]

| Variable | Mean | Standard deviation | Median | Minimum | Maximum |
|---|---|---|---|---|---|
| **Both River Systems, n = 36** | | | | | |
| Reach sinuosity | 1.29 | 0.22 | 1.25 | 1.04 (Beech) | 2.10 (Pigeon) |
| Bank vegetation index | 0.76 | 0.14 | 0.77 | 0.40 (Pigeon) | 0.98 (Middle) |
| Severely eroding banks (percent) | 16 | 11 | 15 | 0 (Middle) | 44 (Calf) |
| Moderately and severely eroding banks (percent) | 43 | 18 | 41 | 14 (Middle) | 86 (Calf) |
| Glide canopy cover (percent) | 56 | 22 | 56 | 7 (Little Buffalo) | 92 (Brush) |
| **Buffalo River System, n = 19** | | | | | |
| Reach sinuosity | 1.28 | 0.20 | 1.20 | 1.04 (Beech) | 1.70 (Bear) |
| Bank vegetation index | 0.85 | 0.09 | 0.86 | 0.68 (Cecil) | 0.98 (Middle) |
| Severely eroding banks (percent) | 16 | 12 | 15 | 0 (Middle) | 69 (Calf) |
| Moderately and severely eroding banks (percent) | 46 | 21 | 39 | 14 (Middle) | 86 (Calf) |
| Glide canopy cover (percent) | 59 | 21 | 60 | 7 (Little Buffalo) | 92 (Brush) |
| **Current River System, n = 17** | | | | | |
| Reach sinuosity | 1.31 | 0.25 | 1.30 | 1.10 (Blair) | 2.10 (Pigeon) |
| Bank vegetation index | 0.66 | 0.11 | 0.68 | 0.40 (Pigeon) | 0.81 (Mill) |
| Severely eroding banks (percent) | 17 | 10 | 19 | 2 (Blair) | 34 (Rogers) |
| Moderately and severely eroding banks (percent) | 41 | 14 | 44 | 18 (Buffalo) | 68 (Spring Valley) |
| Glide canopy cover (percent) | 53 | 23 | 53 | 19 (Gladden) | 90 (Carter) |

## Relations between Channel Stability and Drainage-basin Characteristics

### Correlation Analysis

Scatter plots and correlation analysis illustrate relations between channel stability variables and basin-scale variables. Table 24 shows correlation coefficients for all study drainage basins grouped together and separated into Buffalo and Current groups. Perhaps because of the scale issues described above, sinuosity and canopy cover estimates show few strong correlations. Bank erosion and vegetation measures, however, show correlations in a similar pattern to the channel substrate measures. Correlations are strongest for the combined set of all study drainage basins and for the Buffalo River system.

As with other reach variables, bank vegetation and erosion measures show correlations with relief and land-use variables (fig. 36). Bank vegetation is positively correlated with relief elements and negatively correlated with cleared land area (fig. 36A, B). The measures of bank erosion show related trends. Eroding banks are negatively correlated with relief variables and positively correlated with cleared land area (fig. 36C, D). This suggests that in the Buffalo River system, the lower-relief drainage basins with more cleared land area also have a greater proportion of eroding banks. The correlations with relief and land use are similar to many of those found for the substrate variables and present a similar challenge – relief elements and the proportion of cleared land are correlated basin-scale variables and it is difficult to isolate the influence of one from another. Our description of bedrock banks as "100 percent vegetated, no erosion" also creates the possibility that the trends relate to the greater abundance of streamside bedrock in the higher relief basins, rather than to bank erosion rates.

### Multiple Regression

The only significant multiple regression models we found were for the

**Table 23.** Spearman rank correlation coefficients for relations between reach-stability variables
[shaded values significant at p ≤ 0.05; bold values > 0.5 or < -0.5; refer to Table 5 for variable definitions]

| Variable | Reach sinuosity | Bank vegetation index | Severely eroding banks | Moderately and severely eroding banks | Glide canopy cover |
|---|---|---|---|---|---|
| **Both River Systems, n = 36** | | | | | |
| Reach sinuosity | **1.00** | | | | |
| Bank vegetation index | 0.11 | **1.00** | | | |
| Severely eroding banks | -0.06 | -0.49 | **1.00** | | |
| Moderately and severely eroding banks | 0.00 | -0.31 | **0.79** | **1.00** | |
| Glide canopy cover | -0.17 | 0.16 | 0.11 | 0.20 | **1.00** |
| **Buffalo River System, n = 19** | | | | | |
| Reach sinuosity | **1.00** | | | | |
| Bank vegetation index | 0.09 | **1.00** | | | |
| Severely eroding banks | -0.35 | **-0.84** | **1.00** | | |
| Moderately and severely eroding banks | -0.17 | **-0.82** | **0.81** | **1.00** | |
| Glide canopy cover | -0.25 | 0.08 | 0.04 | 0.11 | **1.00** |
| **Current River System, n = 17** | | | | | |
| Reach sinuosity | **1.00** | | | | |
| Bank vegetation index | 0.36 | **1.00** | | | |
| Severely eroding banks | 0.28 | -0.37 | **1.00** | | |
| Moderately and severely eroding banks | 0.27 | -0.25 | **0.80** | **1.00** | |
| Glide canopy cover | -0.12 | 0.05 | 0.32 | 0.28 | **1.00** |

combined set of study drainage basins (table 25). The models generally mimicked correlation analyses but included an indicator variable demonstrating a difference between the Buffalo and Current river systems. Current River tributaries tend to have both less bank vegetation and fewer eroding banks. There were no significant models with both drainage-basin relief and land-use explanatory variables. As in many of the substrate and channel geometry models, the basin-scale variables appear to act as proxy variables for each other and we were not able to isolate the influence of land use from differences in drainage-basin relief elements.

## Summary of Tributary Reach Analyses

In summary, reach-scale investigations found that habitat conditions vary in ways that are consistent with the physiographic and geologic differences between the Current and Buffalo river systems. Current River tributaries tend to have smaller channel dimensions and finer substrate, characteristics that are consistent with two ways drainage basins characteristics may influence stream channels (table 1). Data support both the hypothesis that flashy storm flows in the more rugged Buffalo River system create larger channels and that the prevalence of karst in the Current drainage basins creates smaller channels.

When study drainage basins were subset by river system, more subtle relations between reach-scale characteristics and drainage-basin variables became apparent. In the Buffalo, tributaries with large proportions of carbonate bedrock and cleared land in their drainage basins have shallow channel dimensions with well-sorted, gravel-rich substrates. These findings are consistent with two additional hypotheses for drainage basin controls on stream channels, that carbonate bedrock reduces storm flow and produces a greater supply of chert gravel to streams, and that cleared land and pasture increase erosion and sediment supply (table 1). Relations for the Current River subset support the hypothesis that karst hydrology exerts a strong influence on Current River tributaries by reducing transport capacity relative to sediment supply. Karst-rich west Current tributaries have smaller channel dimensions, steeper reach gradients, and finer and more embedded substrate than the middle and east Current tributaries.

Many correlations and multiple regression models suggested a link between land use and stream characteristics. For both the combined set of study basins and for separate river system groups, bankfull and residual pool depths are negatively associated with cleared land area. Correlations and multiple regression models also show significant relations between substrate and land-use variables. For the combined set of study basins, finer particle sizes and a higher proportion of gravel are positively associated with cleared land area. When basins were subset, these relations persist within the Buffalo and west Current drainage-basin groups. Both of these findings support the hypothesis that land clearing in the Ozarks increases erosion and the supply of chert gravel to streams (tables 1-2).

The limitation of these relations is that in many cases land-use variables are correlated with other drainage-basin characteristics that influence streams. In both the Buffalo and the Current river systems, drainage basins with steeper average slopes have little cleared land area. Basins with abundant carbonate bedrock also tend to have a high proportion of cleared land area. Only multiple regression models for gravel and cobble/boulder substrate in the thalweg were significant when they included all three types of explanatory variables: geology, relief, and land use. A shift from cobble/boulder to gravel substrate is associated with an increase in cleared land area after accounting for differences in carbonate bedrock area and the proportion of streamside bluffs. This relation was strongest for the Buffalo River system.

## Results: Main Stem Gravel-bar Distributions

The objective of this section is to document the distribution of gravel bars along the main stem Current and Buffalo Rivers, and to explore physiographic and land-use factors which may be responsible, in part, for their distribution. In particular, we are interested in assessing whether the segment-scale distribution of gravel bars in these rivers is an indicator of landscape disturbance in tributary drainage basins.

The distribution of gravel-bars along a river can be affected by at least three sets of processes. At the scale of riffle-pool sequences, gravel is expected to be distributed in lateral or point bars, and would be expected to vary longitudinally at scales of 10-14 channel widths. This will be referred to as reach-scale variability.

Superimposed on the reach-scale variability in gravel distribution would be concentrations of gravel that result from hydraulic interactions at the valley scale. Channel patterns of Ozarks streams (fig. 8) are characterized by juxtaposed stable and disturbance reaches (Jacobson, 1995). The disturbance reaches originally were called sedimentation zones by Saucier (1983), and they are similar to sedimentation reaches described by Church (1983) in British Columbia. Because these reaches are characterized by erosion as well as sedimentation – and to avoid the perception that they are dominated by sedimentation alone – we have elected to call them disturbance reaches. Church (1983) determined that the sedimentation reaches in British Columbia were caused mostly by external factors such as increased sediment load at tributary junctions. In the Ozarks, however, disturbance reaches are independent of tributary junctions, inputs of sediment from hillslope erosion, or structural and lithologic bedrock controls. Stable reaches tend to be long and straight, and the channel usually is adjacent to the valley wall on one side. The other side of the channel, however, is

Calf Creek, Buffalo River tributary

Pigeon Creek, Current River tributary

**Figure 35.** Many study reaches have sections of severely eroding banks with near vertical faces and protruding roots.

**Table 24.** Spearman rank correlation coefficients for relations between reach-stability variables and drainage-basin variables

[shaded values significant at p ≤ 0.05; bold values > 0.5 or < -0.5; refer to Table 5 for variable definitions]

| Variable | Carbonate bedrock area | Drainage area | Drainage basin shape | Elevation range | Drainage basin average slope | Bluff area in stream buffer | Cleared land area | Steep, cleared land area | Cleared land in stream buffer | Road density | Road density in stream buffer |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Both River Systems, n = 36** | | | | | | | | | | | |
| Reach sinuosity | 0.15 | 0.38 | 0.21 | 0.05 | -0.05 | 0.02 | 0.07 | 0.15 | 0.19 | 0.40 | 0.00 |
| Bank vegetation index | -0.27 | -0.11 | -0.23 | **0.57** | **0.64** | 0.50 | -0.23 | 0.24 | -0.47 | -0.15 | -0.07 |
| Severely eroding banks | 0.06 | 0.00 | 0.30 | -0.02 | -0.33 | -0.37 | 0.31 | 0.13 | 0.29 | 0.15 | -0.01 |
| Moderately and severely eroding banks | 0.01 | 0.09 | 0.26 | 0.12 | -0.30 | -0.38 | 0.44 | 0.29 | 0.38 | 0.28 | 0.08 |
| Glide canopy cover | 0.23 | **-0.52** | -0.18 | 0.04 | 0.18 | -0.21 | -0.27 | -0.13 | -0.32 | -0.07 | 0.14 |
| **Buffalo River System, n = 19** | | | | | | | | | | | |
| Reach sinuosity | 0.11 | **0.62** | 0.23 | 0.11 | -0.21 | 0.22 | 0.29 | 0.37 | 0.50 | 0.40 | 0.13 |
| Bank vegetation index | -0.14 | -0.12 | -0.13 | -0.02 | **0.63** | 0.41 | **-0.71** | **-0.51** | **-0.55** | -0.08 | -0.01 |
| Severely eroding banks | 0.11 | 0.02 | 0.21 | 0.07 | -0.49 | -0.38 | 0.50 | 0.36 | 0.33 | 0.06 | 0.02 |
| Moderately and severely eroding banks | 0.21 | 0.15 | 0.25 | 0.19 | **-0.51** | -0.46 | **0.66** | 0.43 | **0.62** | 0.29 | 0.27 |
| Glide canopy cover | **0.54** | -0.45 | -0.19 | -0.31 | 0.07 | -0.34 | -0.02 | 0.09 | -0.25 | 0.21 | 0.24 |
| **Current River System, n = 17** | | | | | | | | | | | |
| Reach sinuosity | 0.17 | 0.18 | 0.07 | 0.19 | 0.25 | -0.11 | -0.18 | 0.07 | -0.18 | 0.43 | -0.19 |
| Bank vegetation index | 0.05 | 0.22 | -0.21 | 0.03 | 0.14 | 0.29 | -0.30 | -0.07 | -0.48 | -0.15 | -0.05 |
| Severely eroding banks | -0.04 | -0.04 | 0.37 | 0.04 | -0.15 | -0.39 | 0.11 | -0.16 | 0.16 | 0.36 | -0.09 |
| Moderately and severely eroding banks | -0.26 | 0.07 | 0.33 | -0.02 | -0.29 | -0.46 | 0.14 | -0.13 | 0.09 | 0.32 | -0.12 |
| Glide canopy cover | 0.07 | **-0.56** | -0.12 | 0.08 | 0.21 | -0.25 | -0.49 | **-0.59** | -0.38 | -0.32 | 0.20 |

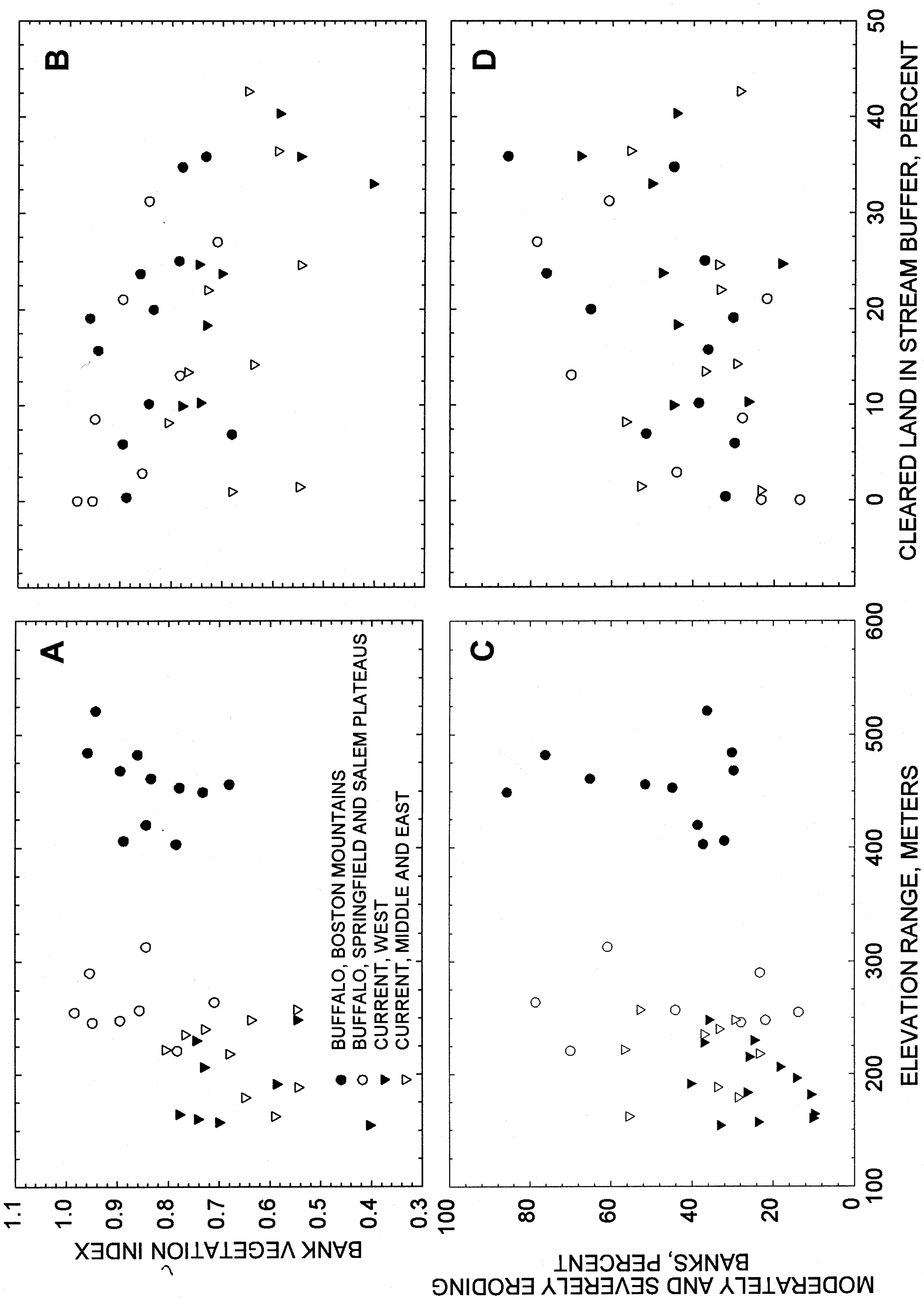



**Figure 36**. Selected scatter plots showing relations between channel stability variables and drainage-basin variables.

**Table 25.** Selected multiple regression models for reach-stability variables and all study drainage basins; explanatory variables signficant at p ≤ 0.05; n = 36

[m, meters; $m^2$, square meters]

| Response variable | Intercept | Model coefficients for explanatory variables | | | | | R squared |
|---|---|---|---|---|---|---|---|
| | | | Physiography | | Land use | | |
| | | Indicator for river system[1] | Drainage basin average slope, in degrees | Bluff area in stream buffer, as a proportion[2] | Cleared land area, as a proportion | Cleared land in stream buffer, as a proportion | |
| Bank vegetation index | 0.6501 | -0.1352 | 0.0181 | | | | 0.59 |
| | 0.7860 | -0.1600 | | 0.7058 | | | 0.57 |
| | 0.9253 | -0.2044 | | | -0.4268 | | 0.63 |
| | 0.9108 | -0.1732 | | | | -0.3742 | 0.62 |
| Moderately and severely eroding banks, as a proportion | 0.8856 | -0.1716 | -0.0385 | | | | 0.25 |

[1] Indicator variable specifies river system, Buffalo = 0 or Current = 1.

[2] Variable was transformed, squareroot(x).

frequently adjacent to a broad, erodible, alluvial valley bottom; hence, the straight reaches do not appear to be constrained by bedrock control. Disturbance reaches are characterized by high sinuosity, frequent channel migration of as much as 250 m in 50 years (Jacobson and Pugh, 1997), and extensive, unvegetated gravel bars. Disturbance reaches apparently result from hydraulic interactions between the channel and the valley wall that cause localized constrictions, expansions, and flow separations at discharges substantially greater than bankfull. Analysis of the longitudinal distribution of gravel-bar area in the Current River demonstrated that disturbance reaches are spaced at distances along the channel much greater than would be expected for meanders or alternate bars at the reach scale (Jacobson and Gran, 1997).

Finally, at the segment-scale, longitudinal distribution of gravel may indicate effects of variable sediment delivery from tributary drainage basins. The difficulty is in factoring out valley-scale effects and resolving the effects of transient gravel transport from synoptic measurements. In the following sections we present gravel-bar area distribution data from two dates on the Current River (March 1992 and April 1996) and one date on the Buffalo River (March 2000), and assess relations between these data and possible valley-scale controls. Next, we analyze possible linkages between geologic, physiographic, and land-use characteristics of tributary drainage basins, and gravel-bar area inventories. Finally, we compare these new results with previous work that supported the idea that transient gravel transport in Ozarks streams would obscure most links between land use and gravel distributions:

> "Tributary basin characteristics may well have an effect on gravel distributions, but within the range of variation that exists in the Current River Basin, only weak tributary effects are measurable. Present-day land use seems to be much less important than the propagating effects of historical land use in determining the present-day gravel distribution. Local hydraulic interactions between the channel and the valley-although poorly understood-exert a secondary effect, resulting in discrete gravel accumulations at the scale of disturbance reaches." (Jacobson and Gran, 1997).

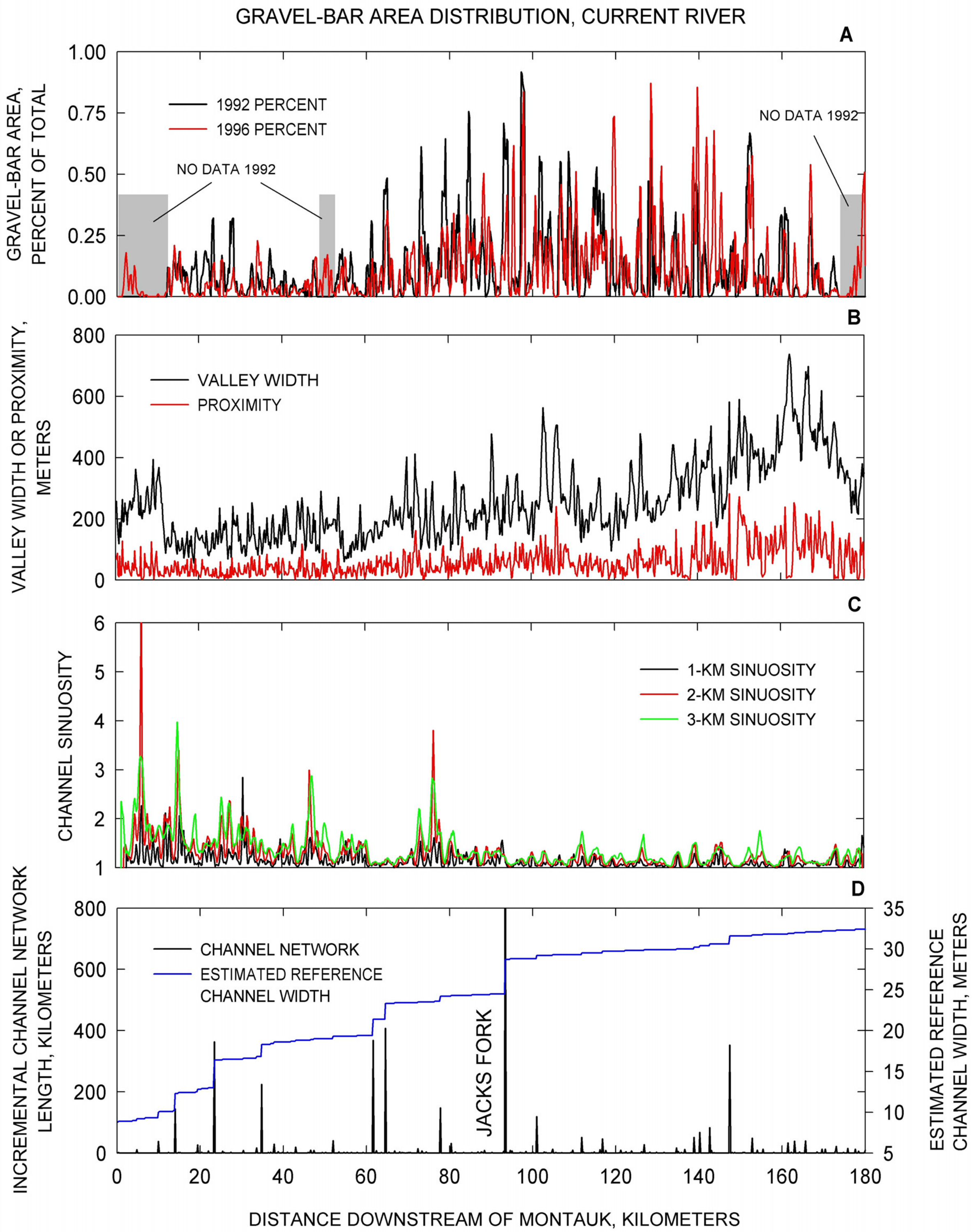



**Figure 37.** A. Plots of gravel-bar area along Current River, 1992 and 1996, as percent of total gravel-bar area in each year. B. Plots of valley width and proximity of channel to valley wall along the Current River. C. Plots of sinuosity along Current River, using 1-km, 2-km, and 3-km rulers. D. Plots of incremental channel network length (a surrogate for incremental drainage area) and estimated channel width along the Current River.

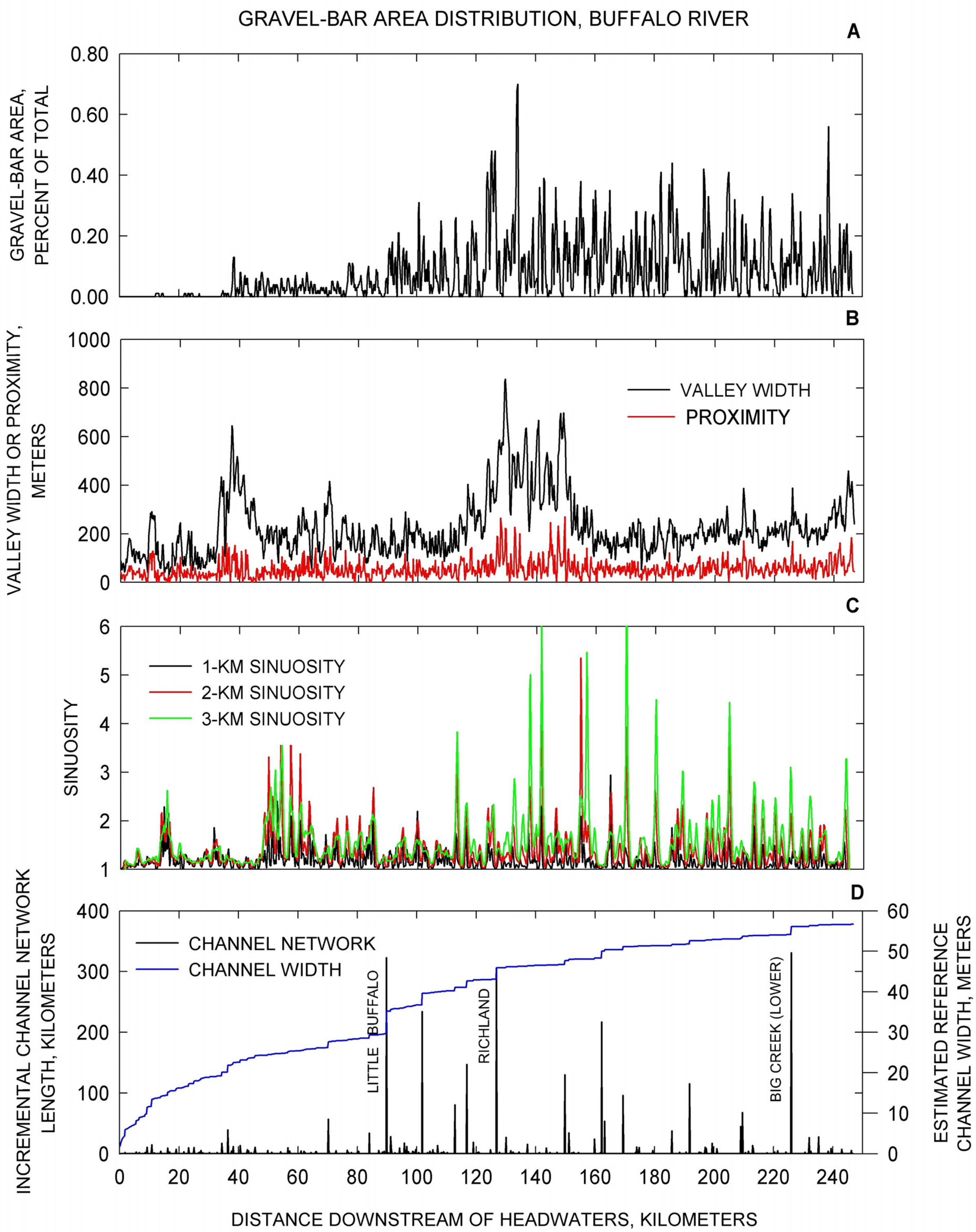



**Figure 38.** A. Plots of gravel-bar area along Buffalo River, 2000, as percent of total gravel-bar area. B. Plots of valley width and proximity of channel to valley wall along the Buffalo River. C. Plots of sinuosity along Buffalo River, using 1-km, 2-km, and 3-km rulers. D. Plots of incremental channel network length (a surrogate for incremental drainage area) and estimated channel width along the Buffalo River. Headwaters reference point is upstream end of main-stem channel.

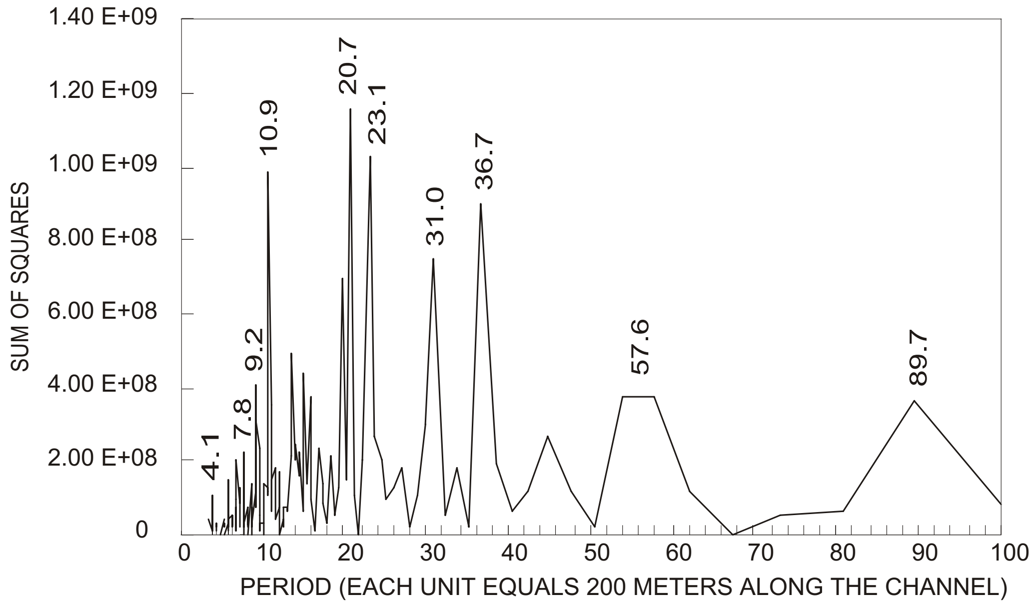



**Figure 39.** Plot of results of spectral analysis of Current River gravel, 1992, showing variance, as sum of squares by period - each period is equal to 200 meters along the river channel.

## Valley-scale Controls on Longitudinal Gravel-bar Distributions

Longitudinal inventories of gravel-bar area in the Current and Buffalo Rivers were compiled and plotted to compare with potential valley-scale and tributary influences. Plotting by 200-m longitudinal addressing system provides a nearly continuous set of classification variables over hundreds of kilometers (figs. 37-38).

### Current River

The longitudinal distribution of gravel on the Current River main stem in 1992 showed high-frequency variation and a broad wave-like form centered just downstream of the confluence of the Jacks Fork River (fig. 37). Jacobson and Gran (1997) analyzed the spectral characteristics of this distribution and determined three significant quasi-periodic signals (99 percent confidence limit) at 1,860, 2,155, and 4,015 m (fig. 39). If these prominent spectral peaks were related to channel meanders, they would be expected to have a spacing of about 11 to 16 times the channel width, according to conventional channel-geometry models (Leopold and others, 1964). For the typical range of bankfull widths on this segment of the Current River, this spacing would range from 70 to 450 m. Because the prominent spacings at 1,860-4,015 m (and greater) are at a substantially greater spacing than would be expected from channel meandering, Jacobson and Gran (1997) concluded that they are associated with a different process, probably controlled in part by valley-scale hydraulic constraints.

Valley-scale characteristics that might cause accumulations in disturbance reaches were evaluated by analyzing statistical relations between gravel-bar area and valley-scale variables (figs. 37, 40A-F). Relations between gravel-bar area at addresses and two measures of channel confinement (valley width and distance from channel to valley wall) indicate envelope, bounding relations in which maximum values of gravel-bar area are associated with narrow to moderate values of channel confinement (figs. 40A, B). Inverse relations of gravel-bar area with channel sinuosity measured at three scales (1-, 2-, and 3-kilometer) indicate an envelope relation in which some – but not all – of the highest gravel concentrations are associated with low channel sinuosity. The longitudinal distribution of channel-confinement variables and sinuosity variables shows that they vary in opposite directions along the river (fig. 37).

The longitudinal distribution of gravel along the Current River (fig. 37A) does not increase monotonically downstream as a function of increasing drainage area as would be expected if gravel-bar area related directly to channel width (fig. 37D). Although the distribution

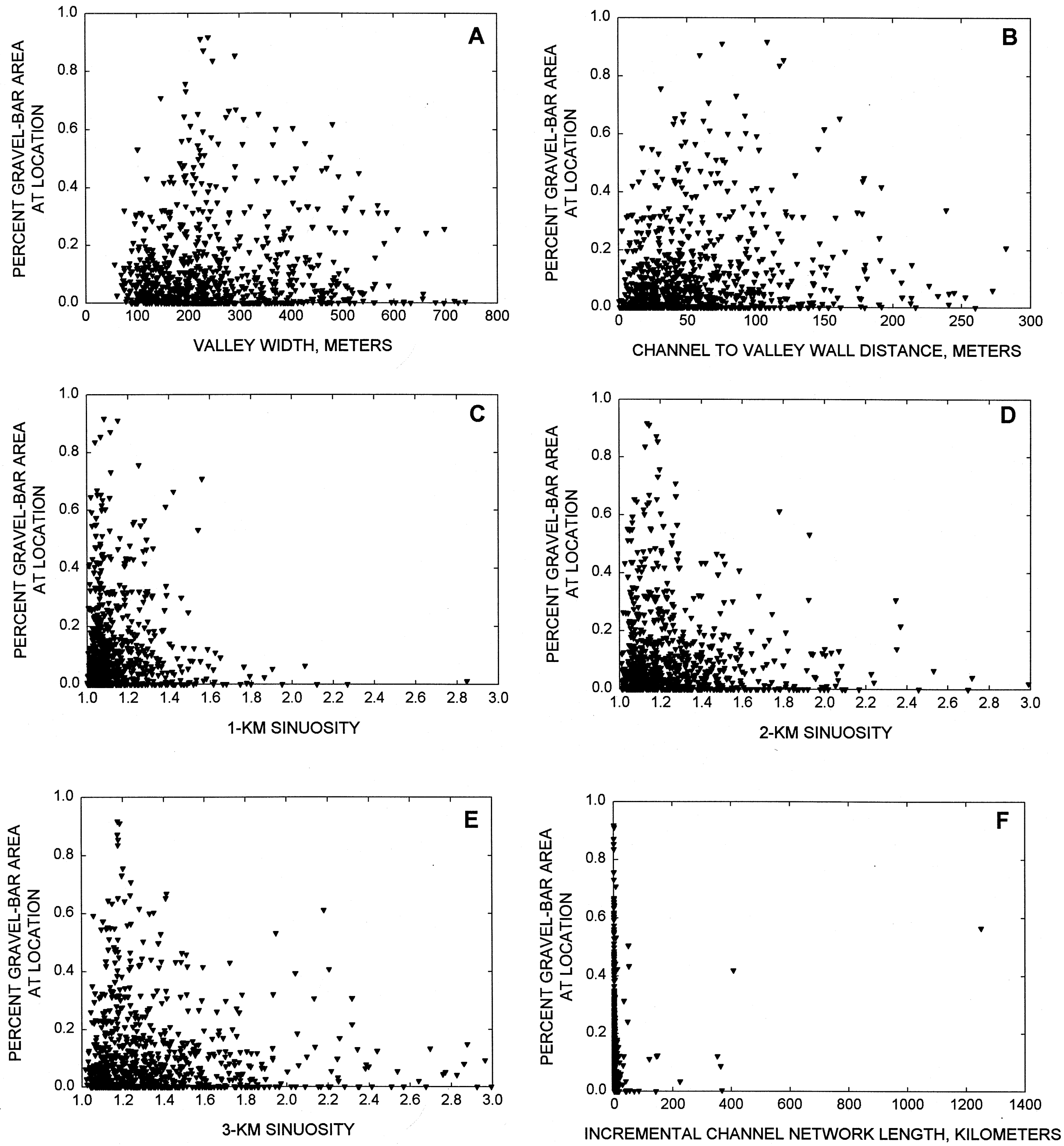



**Figure 40.** Scatter plots of gravel-bar area and valley-scale variables, 1992 gravel-bar inventory, Current River. A. Percent gravel-bar area plotted against valley width. B. Percent gravel-bar area plotted against proximity (distance from channel to valley wall). C. Percent gravel-bar area plotted against 1-km sinuosity. D. Percent gravel-bar area plotted against 2-km sinuosity. E. Percent gravel-bar area plotted against 3-km sinuosity. F. Percent gravel-bar area plotted against incremental channel-network length.

increases generally around and downstream of the Jacks Fork confluence, (fig. 37A), gravel-bar area at individual address points show weak associations with a measure of incremental drainage area (measured as incremental channel network length at each address point, fig. 40F). This last relation is not unexpected for individual address points: gravel contributed by tributary drainage basins would be expected to disperse and translate for some distance downstream from points where it is delivered to the channel.

#### Current River Temporal Comparison

Aerial photographs from 1992 and 1996 provide a unique opportunity to compare longitudinal gravel distribution changes over time, and to evaluate a conceptual model of gravel routing presented by Jacobson and Gran (1997). As discussed in the methods section, discharge during March 8, 1992 was somewhat less than that of April 16, 1996 (figs. 9A-D; table 6). However, channel width is fairly insensitive to discharge over this range of discharges (fig. 10), and normalization of the data by dividing by the total gravel-bar area mapped on each date serves to minimize bias from variable discharge.

The change in gravel distribution between the two dates of photography is of interest in view of Jacobson and Gran's (1997) simple model that produced a longitudinal distribution of gravel by simply routing gravel "packets" through the channel network uniformly through time (fig. 41). Although the time frame was uncalibrated, the heuristic model produced longitudinal distributions remarkably similar to mapped distributions (especially around timesteps 13-15), and predicted continued downstream translation and growth of wavelike gravel accumulations. The change in gravel distributions in this time period is also of great interest because of a flood of estimated 50-year recurrence interval that occurred in November, 1993 (fig. 9A, B).

Comparison of 25-point moving averages of gravel distributions in 1996 and 1992 indicates substantial downstream translation of gravel, especially losses of gravel at km 90-110 and gains at km 125-150 (fig. 42A, B). These data suggest a downstream translation of as much as 50 km. Differences (1992 minus 1996) of the non-averaged data show sharp peaks of loss and gain, suggestive of exchange of gravel between disturbance reaches. Dominant losses occur in peaks at km 90-110 and gains km 125-150. Jacobson and Gran (1997) remarked that the 1992 distribution resembled the modeled distribution at timesteps 7-9. After the estimated 50-year flood of the intervening years, the 1996 distribution resembles the modeled distribution at timesteps 13-15 (fig. 41).

#### Buffalo River

The distribution of gravel along the Buffalo River main stem also is highly variable at a range of scales (fig. 38); the broader-scale distribution is apparent in the 25-point moving average (fig. 43). Upstream of km 30 the river is in a narrow valley within the Boston Mountains and there is little gravel-bar accumulation. Downstream of km 30 in the Boxley Valley, where the valley is underlain by the Ordovician St. Peter Sandstone and Everton Formation, the valley widens out and gravel bars become apparent. Gravel-bar area increases slightly in the downstream direction until approximately km 89. At that point, the Little Buffalo River enters the main stem and gravel-bar area increases substantially. There is another increase in gravel-bar area at the confluence with Big Creek (upper) at km 102. Around km 123 the river crosses from Ordovician rocks to the Mississippian Boone Formation. At this point, the valley widens from an average of about 200 m to as much as 800 m and gravel-bar area increases markedly; this increase also is associated with the entrance of Richland Creek at about km 127. The largest spike in the non-averaged longitudinal distribution is at km 134, just downstream from Richland Creek.

From km 140 to the mouth the distribution is characterized by high-frequency variation similar to that on the Current River, and presumably related to valley-scale hydraulic interactions. The second largest spike in the non-averaged gravel-bar area distribution is at km 234, about 8 km downstream of the confluence of Big Creek (lower).

Valley-scale characteristics that might influence the longitudinal distribution were evaluated by analyzing statistical relations between gravel-bar area and valley-scale variables (figs. 38, 44A-F). Relations between gravel-bar area at addresses and two measures of channel confinement (valley width and distance from channel to valley wall) indicate envelope relations similar to the Current River in which some – but not all – of the highest longitudinal concentrations of gravel are associated with narrow-moderate confinement (figs. 44A, B). In contrast to the Current River, however, the largest gravel-bar areas are associated with valley widths of 400-600 m, indicating that wider valleys provide more potential for gravel accumulation. Inverse relations of gravel-bar area with channel sinuosity measured at three scales (1-, 2-, and 3-kilometer) indicate an envelope tendency in which some – but not all – high gravel concentrations are associated with low channel sinuosity (figs. 44D, E, F). The inverse relations are not as pronounced as those on the Current River, however, as greater relative gravel area is associated with greater sinuosity values, especially at the 3-kilometer scale.

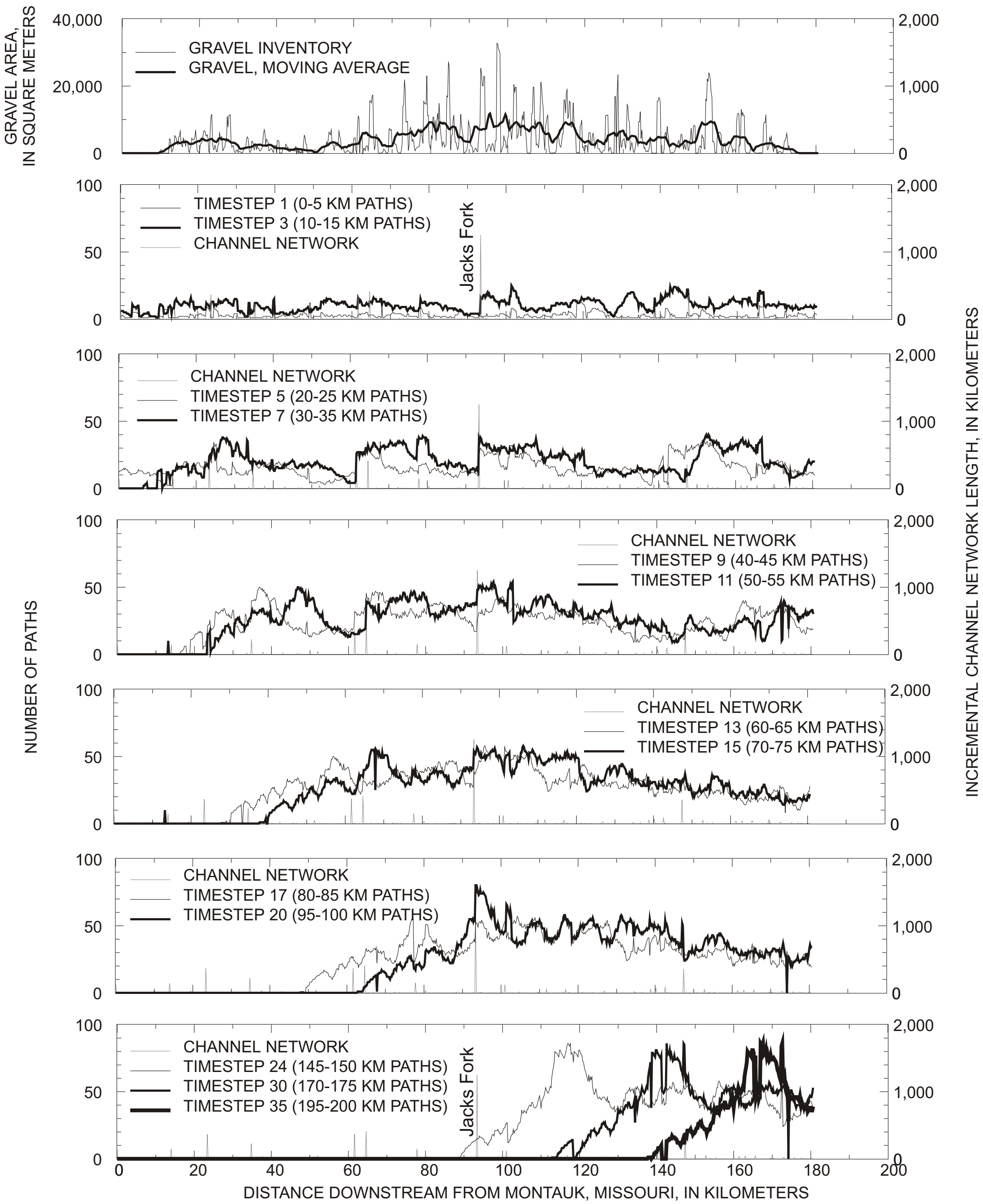



**Figure 41.** Plots of gravel-bar area and simple routing model results at 13 time steps (from Jacobson and Gran, 1999). Timesteps are uncalibrated measures of transport time; historical observations suggest a time step may be approximately 10 years. Number of paths is an indirect measure of gravel 'packets' potentially delivered to the main-stem address points at a given time step.

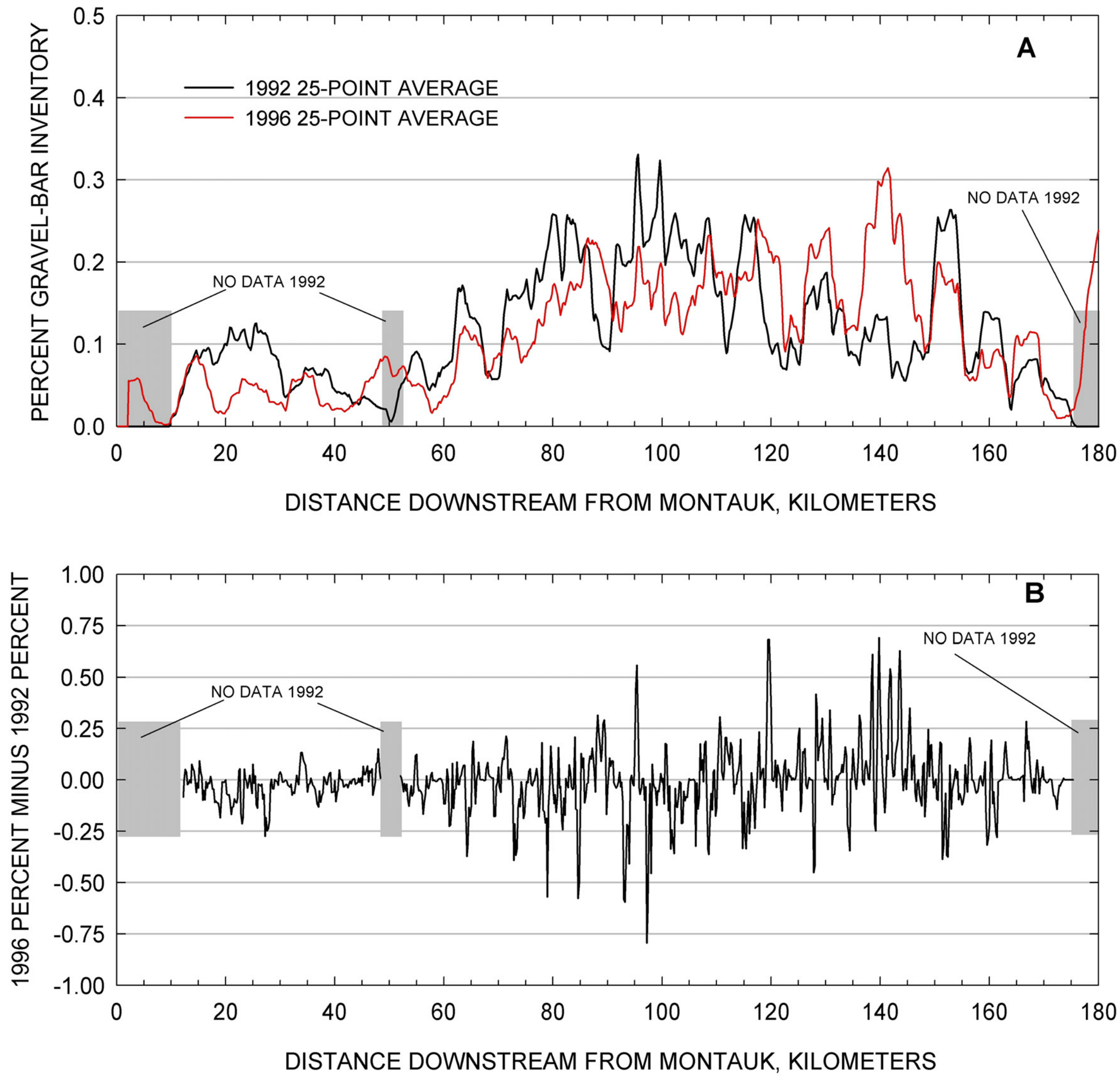



**Figure 42.** 25-point moving average of gravel-bar normalized areas plotted against distance downstream for 1992 and 1996, Current River. B. Differences in gravel-bar area inventory 1992 minus 1996 plotted against distance downstream, showing net prominent gravel accumulation downstream of kilometer 120.

The longitudinal distribution of gravel along the Buffalo River does not increase monotonically downstream as a function of increasing drainage area, but does show more correspondence to increasing drainage area than the Current River. Steplike increases in gravel-bar area at major tributary junctions indicate measurable direct effects of the tributary drainage basins (fig. 38). Particularly notable are substantial increases at the junctions of Little Buffalo River, Big Creek (lower), and Richland Creek. Individual address points, however, show weak associations with a measure of incremental drainage area (measured as incremental channel network length at each address point, fig. 44F).

## Relations between Drainage-basin Characteristics and Gravel-bar Distributions

The general hypothesis that main-stem gravel-bar distributions are affected by tributary drainage-basin characteristics is addressed through exploratory statistical analyses of gravel-bar inventories compared to tributary drainage-basin variables. Because gravel delivered from tributaries to the main stem is transported downstream, measures of gravel-bar area must include gravel-bar area summed for some distance downstream. The distance to sum gravel-bar area is not known, and can be considered an additional response variable. Conceptually, the optimal downstream distance for summing would be a function of the time since an episodic introduction of gravel, the quantity of sediment delivered from the tributary, and the relative sediment transport capacity of the tributary and main stem. Arbitrary summing distances of 0.2, 0.4, 0.6, 1.0, 1.6, 2.0, 2.6, 3.0, 3.6, and 4.8 km were used in this analysis. The summed gravel-bar area was normalized by the estimated channel reference width to account for expected downstream trends in gravel-bar area as the channel size increased (figs. 45, 14).

#### Current River

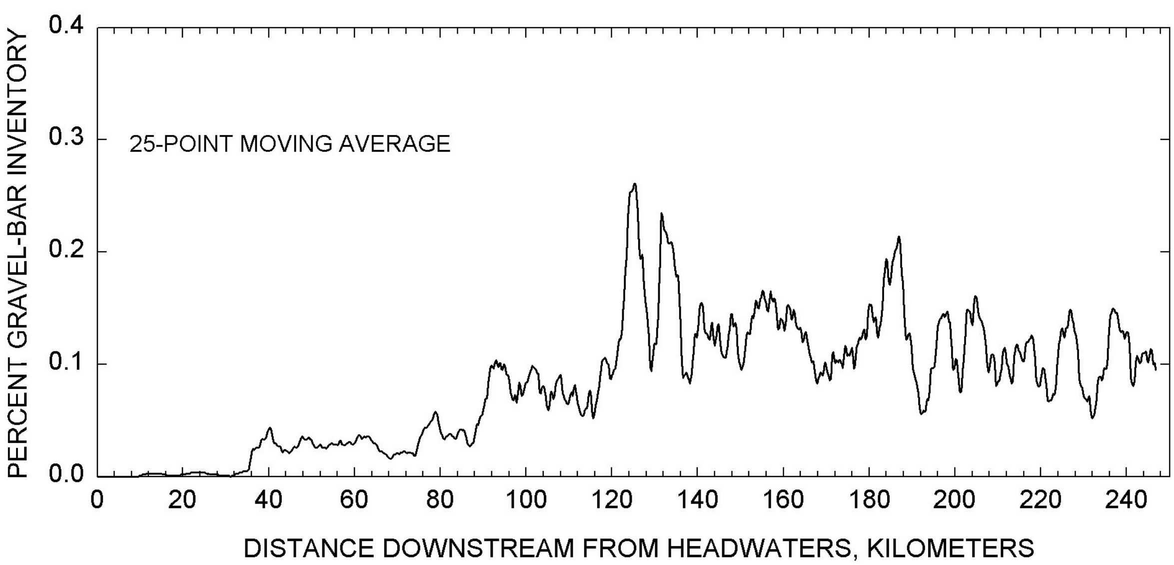
For the analysis of tributary drainage-basin controls on the longitudinal distribution of gravel-bar area on the Current River, we decided to use the 1992 gravel distribution because it was unaffected by the November 1993 flood, an extreme event that caused downstream movement of sediment. Summed, normalized gravel distributions for both dates are shown in figure 45; both show slight diminishment of the relative magnitude of downstream peaks due to normalization.

Correlation analysis was used to explore relations between summed gravel areas and drainage-basin characteristics (table 26). As emphasized in earlier sections of this report, many drainage-basin characteristics are correlated with each other (table 8), so relations with gravel-bar area must to be interpreted with caution.

Three features of the gravel-bar correlations are notable. First, all of the significant correlations are calculated for sums of gravel-bar area over downstream distances of 3.0 km and greater. Second, there are positive correlations with geologic and physiographic variables that might control transport capacity and sediment supply in the tributary drainage basins (carbonate bedrock area, elevation range, and drainage-basin average slope, figs. 46A, B, C). Third, and surprisingly, significant correlations with land-use variables are all negative (figs. 46D, E, F). These relations may result from the strong negative correlations between land-use variables and slope (table 8).

Multiple regression was used to explore trade-offs among variables in explaining summed, normalized gravel accumulations. As with other sections of the report, this level of analysis is not intended to produce predictive models; rather the intent is to identify consistent models for different measures of gravel-bar area. Of the many possible permutations of models that could be developed, we chose the most meaningful based on correlation analysis and an understanding of physical processes operating in the river basins.

From these constraints, only two statistically significant models emerged from the analysis (table 27). One model explains summed, normalized gravel at 4.8 km downstream as a function of two measures of physiographic relief: drainage-basin average slope and elevation range. The second model explains slightly more




25-point moving average of gravel-bar normalized area plotted against distance downstream, Buffalo River.

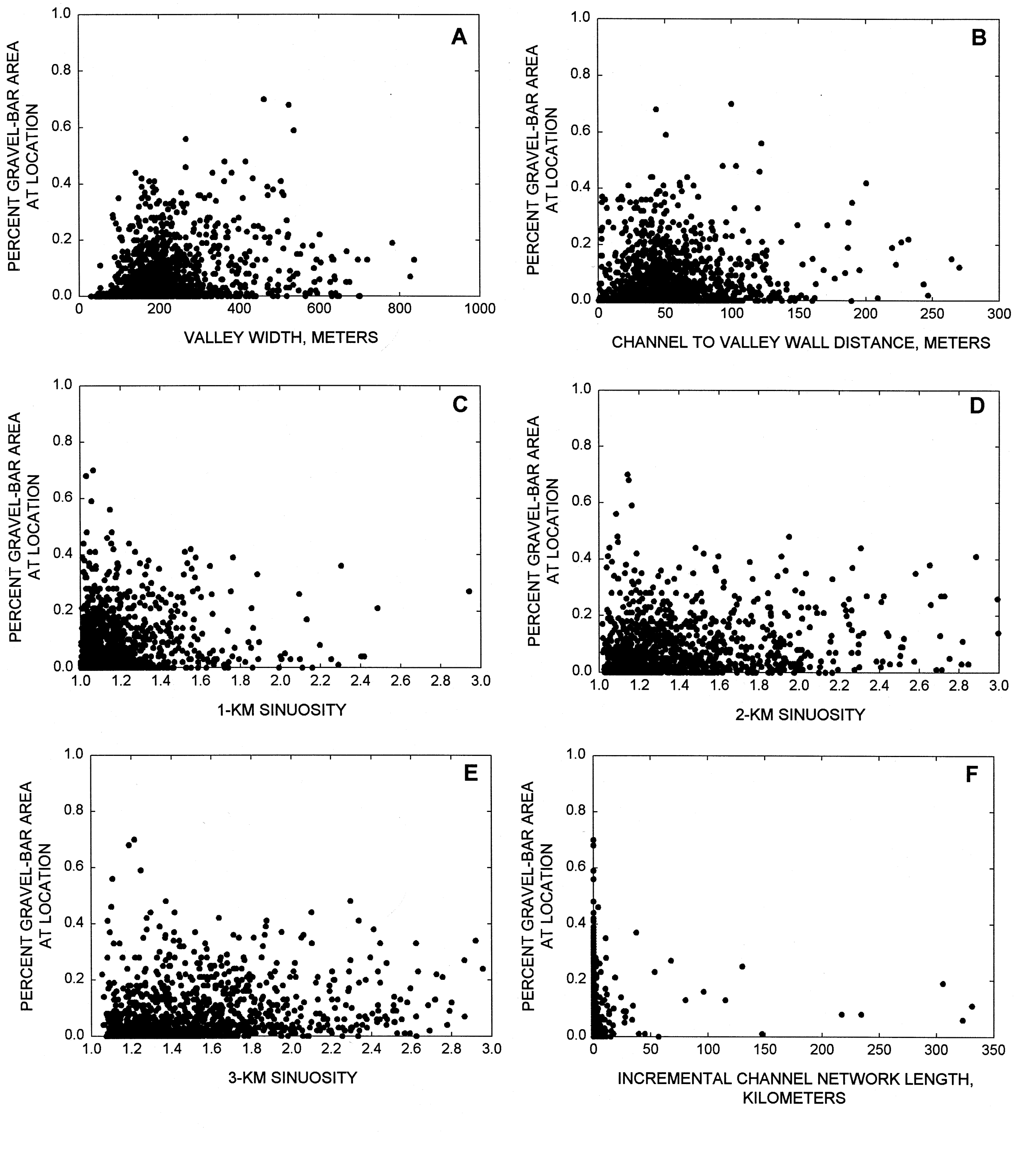
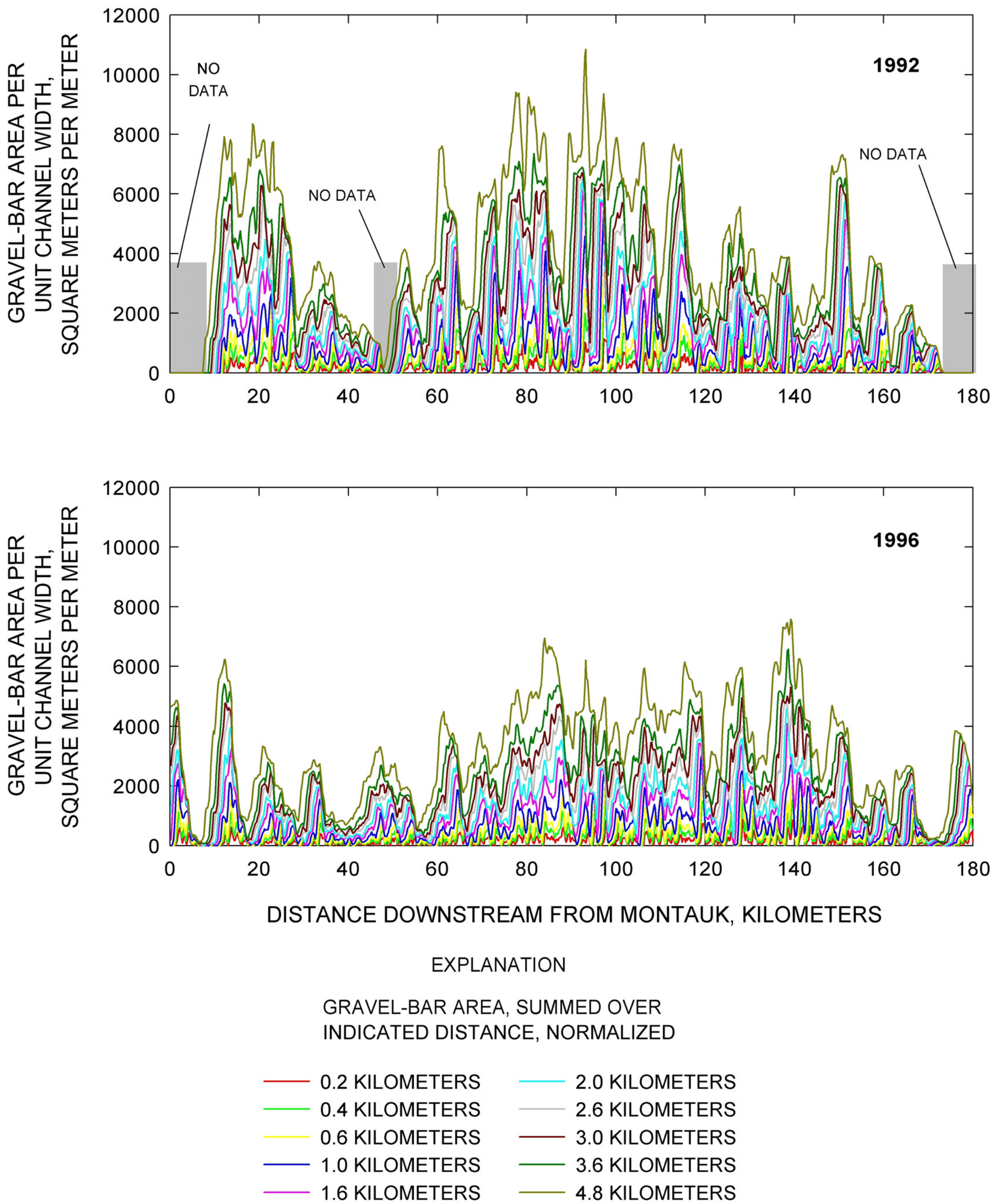



**Figure 44.** Scatter plots of gravel-bar area and valley-scale variables, 2000 gravel-bar inventory, Buffalo River. A. Percent gravel-bar area plotted against valley width. B. Percent gravel-bar area plotted against proximity (distance from channel to valley wall). C. Percent gravel-bar area plotted against 1-km sinuosity. D. Percent gravel-bar area plotted against 2-km sinuosity. E. Percent gravel-bar area plotted against 3-km sinuosity. F. Percent gravel-bar area plotted against incremental channel-network length.




Plots of unit gravel-bar area summed over distances of 0.2 - 4.8 km downstream, plotted against distance downstream

variation and relates summed, normalized gravel at 4.8 km downstream directly to elevation range and inversely to cleared land area. Because of the very strong inverse correlation between steepness and agricultural land use, these models both probably reflect the over-riding contribution of gravel from steep, high-relief basins in the middle and east Current River basin, relatively independent of land-use patterns. It is also possible that relations with land-use variables are related to the distribution of karst networks in the river system. Cleared land is concentrated in west Current drainage basins where karst hydrology and underdrained streams

**Table 26.** Spearman rank correlation coefficients for Current River gravel-bar area against drainage-basin variables

[km, kilometers; shaded values significant at p = 0.05; bold values > 0.5 or < -0.5]

| Variable | | Carbonate bedrock area | Drainage area | Drainage basin shape | Elevation range | Drainage basin average slope | Bluff area in stream buffer | Cleared land area | Steep, cleared land area | Cleared land in stream buffer | Road density | Road density in stream buffer |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Gravel-bar area summed at distances downstream | 0.2 km | -0.28 | -0.20 | -0.26 | -0.11 | -0.27 | -0.02 | 0.18 | 0.25 | -0.10 | 0.23 | -0.37 |
| | 0.4 km | -0.31 | -0.15 | -0.18 | -0.10 | -0.23 | -0.01 | 0.19 | 0.28 | -0.03 | 0.03 | -0.19 |
| | 0.6 km | -0.33 | 0.06 | 0.04 | 0.07 | -0.21 | 0.22 | 0.21 | 0.26 | 0.01 | 0.01 | -0.06 |
| | 1.0 km | 0.05 | -0.09 | 0.17 | 0.19 | 0.12 | 0.17 | -0.08 | 0.02 | -0.15 | -0.12 | -0.01 |
| | 1.6 km | 0.28 | -0.29 | 0.31 | 0.27 | 0.28 | 0.06 | -0.40 | -0.39 | -0.39 | -0.01 | 0.32 |
| | 2.0 km | 0.32 | -0.27 | 0.41 | 0.33 | 0.32 | 0.15 | -0.46 | -0.37 | -0.50 | 0.09 | 0.36 |
| | 2.6 km | 0.28 | -0.17 | 0.40 | 0.38 | 0.28 | 0.21 | -0.39 | -0.25 | -0.45 | 0.15 | 0.35 |
| | 3.0 km | 0.44 | -0.49 | 0.14 | 0.24 | 0.45 | -0.04 | **-0.53** | -0.43 | -0.39 | -0.04 | 0.46 |
| | 3.6 km | **0.59** | -0.50 | 0.13 | 0.34 | **0.53** | -0.08 | **-0.64** | **-0.56** | **-0.50** | -0.03 | 0.46 |
| | 4.8 km | **0.55** | -0.31 | 0.14 | **0.57** | **0.53** | 0.05 | **-0.61** | -0.42 | **-0.51** | -0.02 | 0.42 |

predominate. These basins may lack sufficient transport capacity to introduce large volumes of gravel into the Current River.

The fact that the best relations are for gravel summed 3.0-4.8 km downstream of the tributary confluences (table 26) indicates that in the Current River basin gravel has been transported long distances downstream on the main stem. We believe this may be true either because substantial time has elapsed since the gravel was delivered to the main stem or because main-stem sediment transport capacity is sufficient to move the sediment downstream rapidly.

### Buffalo River

The summed, normalized gravel distribution for the Buffalo River is shaped much like the non-normalized data, but with a slight diminishment of the relative magnitude of downstream peaks due to normalization (fig. 47). Correlation analysis was used to explore summed gravel areas with tributary drainage-basin variables (table 28). Many of the drainage-basin characteristics are also correlated (table 8), so the correlations must be interpreted with caution.

In contrast to the Current River, many of the significant correlations occur for gravel summed within 1 km of the tributary junctions (table 27). For geologic and physiographic variables, a significant correlation exists between carbonate bedrock area and gravel summed at 0.6 km and significant correlations exist for basin shape factor and gravel summed at 3.0-4.8 km (figs. 48A, B). For sums over distances of 0.2-0.6 km, gravel-bar area is negatively correlated with drainage-basin average slope (fig. 48C). Notably, all significant correlations with land-use variables are positive (figs. 48 D, E, F, G, H). Strong negative correlations between average slope and agricultural land-use variables (table 28) complicate the interpretation of these correlations.

A greater number of statistically significant multiple regression models could be compiled to relate gravel-bar area on the Buffalo River compared to the Current River. However, no models with drainage-basin average slope and any of the three land cover variables were significant, or produced more understanding than correlation analysis. At 0.6 km distance downstream, summed, normalized gravel-bar area was modeled as an increasing function of carbonate bedrock area and cleared land area in the stream buffers. The model is notable in combining carbonate bedrock area – which is highly correlated with agricultural land use – and a specific land-use attribute: cleared land in the stream buffer. Gravel summed over 2.0 km downstream was positively correlated with cleared land in the stream buffers and road density in the stream buffers. For gravel summed at 3.0 and 3.6 km downstream, significant models related gravel to drainage-basin shape factors and cleared land in stream buffers (and in one case, slope). Higher values of basin shape factors indicate longer, narrower basins. We have no information on physical processes that might link narrow basin forms to increased sediment delivery.

The fact that most of the significant correlations and multiple regression models are for gravel summed with-

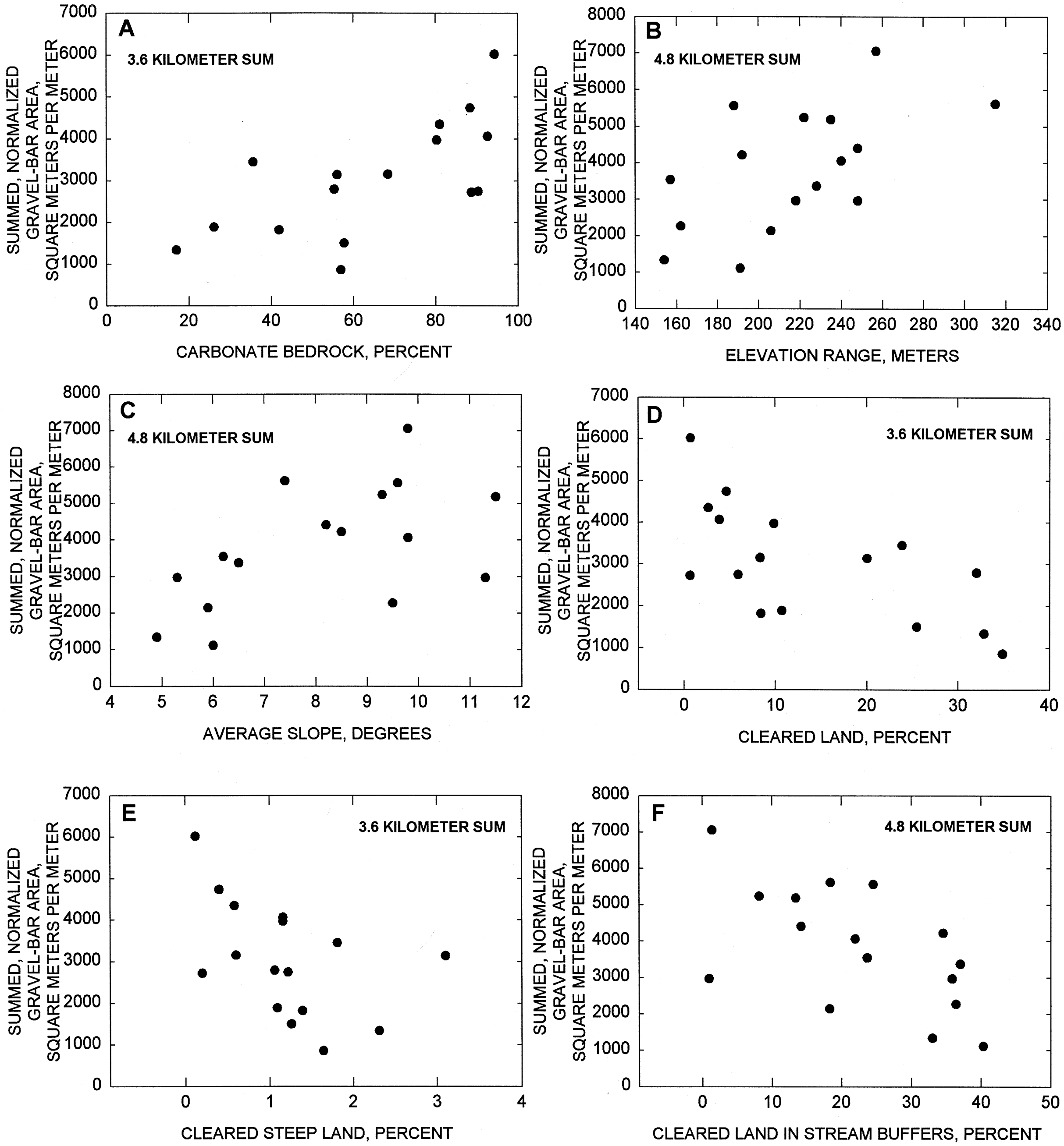



**Figure 46.** Selected scatter plots of drainage-basin characteristics and unit gravel-bar area inventories, Current River. A. Unit gravel-bar area summed 3.6 km downstream plotted against percent carbonate bedrock in basin. B. Unit gravel-bar area summed 4.8 km downstream plotted against drainage-basin elevation range. C. Unit gravel-bar area summed 4.8 km downstream plotted against drainage-basin average slope. D. Unit gravel-bar area summed 3.6 km downstream plotted against cleared land area. E. Unit gravel-bar area summed 3.6 km downstream plotted against steep, cleared land area. F. Unit gravel-bar area summed 4.8 km downstream plotted against cleared land in stream buffers.

**Table 27.** Selected multiple regression models relating gravel-bar area summed at distances downstream from tributary junctions and tributary drainage-basin variables; explanatory variables

[km, kilometers; m, meters; m/m$^2$, meters per square meter]

| Response variable | | Intercept | Model coefficients for explanatory variables: Geology | Physiography | | | Land use | | | R squared |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Carbonate bedrock area, as a proportion | Drainage basin shape factor | Drainage basin average slope, in degrees | Elevation range, in m | Cleared land area, as a proportion | Cleared land in stream buffer, as a proportion | Road density in stream buffer, in m/m$^2$ | |
| **Current River System, n = 16** | | | | | | | | | | |
| Gravel-bar area summed at distances downstream | 4.8 km | -3364.44 | | | 365.04 | 19.57 | | | | 0.55 |
| | | 1113.00 | | | | 17.59 | -7815.49 | | | 0.64 |
| **Buffalo River System, n = 19** | | | | | | | | | | |
| | 0.6 km | 72.09 | 358.39 | | | | | 885.89 | | 0.56 |
| | 2.0 km | 437.88 | | | | | | 2498.19 | 274999 | 0.66 |
| | 3.0 km | 598.94 | | 114.69 | | | | 2533.77 | | 0.62 |
| | 3.6 km | -1243.66 | | 186.36 | 144.58 | | | 3858.45 | | 0.66 |
| | | 756.65 | | 161.10 | | | | 2166.01 | | 0.46 |

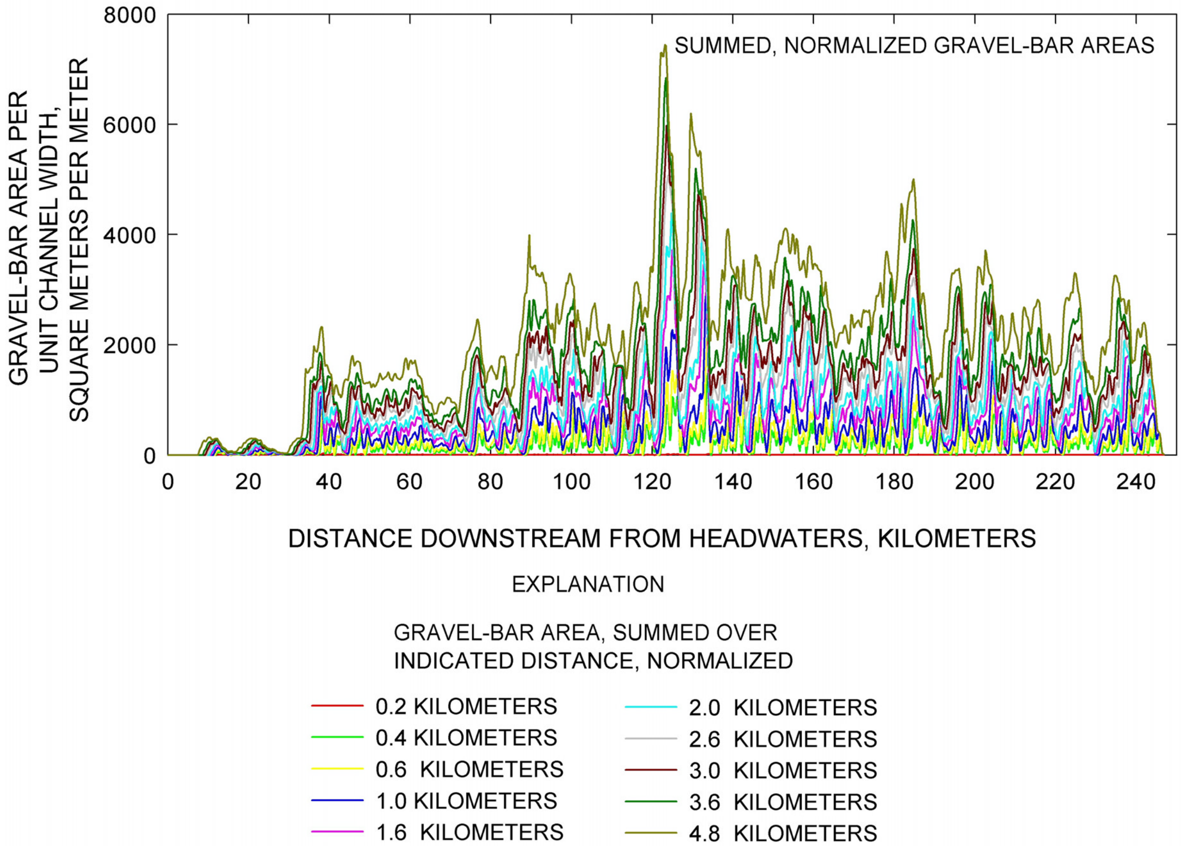
in 1.0 km of tributary confluences suggests that little time or opportunity has existed for transport of the sediment downstream on the main stem. Accumulations close to the confluences may indicate that little time has elapsed since episodic sediment delivery at the confluence, or that sediment delivery in these tributary basins has been increased relative to sediment-transport capacity in the main stem.

## Summary of Main-stem Gravel-bar Analyses

Similar to analysis of the links between drainage-basin characteristics and reach-scale habitats, the analysis of links to segment-scale gravel distributions is complicated by the complex relations among landscape variables. In particular, the relations among carbonate bedrock, relief variables, and land-use variables make it difficult to separate out individual influences. Added to the spatial variation is the additional complication that the response variable – gravel-bar area – is lagged in time from the initiation of disturbance. Hence, the gravel-bar area measured today may not correspond with land-use characteristics measured today. To some extent, temporal lags can be accounted for by summing gravel-bar area downstream, yet how far to sum is itself an unknown and may be highly variable in time and along the river system.

The longitudinal distribution of gravel in the Current and Buffalo Rivers have high-frequency variations that appear to be the result of hydraulic interactions of the channel with valley walls, resulting in gravel accumulations at the scale of disturbance reaches (Jacobson and Gran, 1997). These high frequency accumulations are superimposed on broader scale influences of valley width and tributary influxes.

On the Current River, the effects of tributary influxes are seen in the broad wave-like form associated with the confluence of Jacks Fork (figs. 37, 42A). The direct effects of tributary influxes are diminished by downstream transport of gravel in the main stem, making direct correlations on a point-by-point basis weak (fig. 40G). The simple routing model proposed by Jacobson and Gran (1997; fig. 41) and the comparison of the 1996 distribution to the 1992 distribution (fig. 42A) support the conceptual model that the broadscale distribution of gravel in the Current River results from delivery of excess gravel at tributary junctions and progressive downstream transport. The present-day longitudinal distribution of gravel on the Current River is strongly influenced by lagged effects of spatially varying influxes.




Plot of unit gravel-bar area summed over distances 0.2-4.8 km downstream, plotted against distance downstream, Buffalo . Headwaters reference point is upstream end of main-stem channel.

The conclusions derived from analysis of the longitudinal distribution of gravel also are supported by analysis of the relations between summed gravel-bar areas compared to tributary drainage-basin characteristics (tables 26-28). On the Current River, the best correlations and multiple regression models are for gravel-bar areas summed over 3.0-4.8 km downstream from the tributary confluences. These relations are positive with respect to physiographic and geologic variables and negative with respect to land-use variables. Because of the strong negative correlations among geology, steepness, and agricultural land use, it is difficult to separate out the individual effects of land use. One hypothesis is that large gravel-bar accumulations in the Current River result from gravel delivery from the naturally steep East Current drainage basins. Present-day land-use data (early-mid 1990's) indicate that these drainage basins now have low land-use disturbance potential. The evident, transient influxes of sediment from these tributaries, however, may have resulted from relatively low levels of land-use change in the past. High natural potential for sediment delivery from these basins may be accompanied by relatively low thresholds for disturbance.

On the Buffalo River, valley width appears to combine with tributary influxes to determine the broad-scale influences on gravel accumulations (fig. 38). The abrupt and dramatic change of valley width at km 120-160 where the river flows onto the Mississippian Boone Formation is associated with a steplike increase in gravel-bar area. In addition, steplike increases in gravel-bar area are apparent at major tributary junctions like Little Buffalo River, Big Creek (upper), Richland Creek, and Big Creek (lower) (figs. 38, 43). These step-like increases related to tributary junctions are more apparent on the Buffalo River than on the Current River, indicating that there may be a closer temporal linkage between cause and effect on the Buffalo River. Similar to the Current River, point-by-point correlations of valley-scale effects indicate tremendous variability and

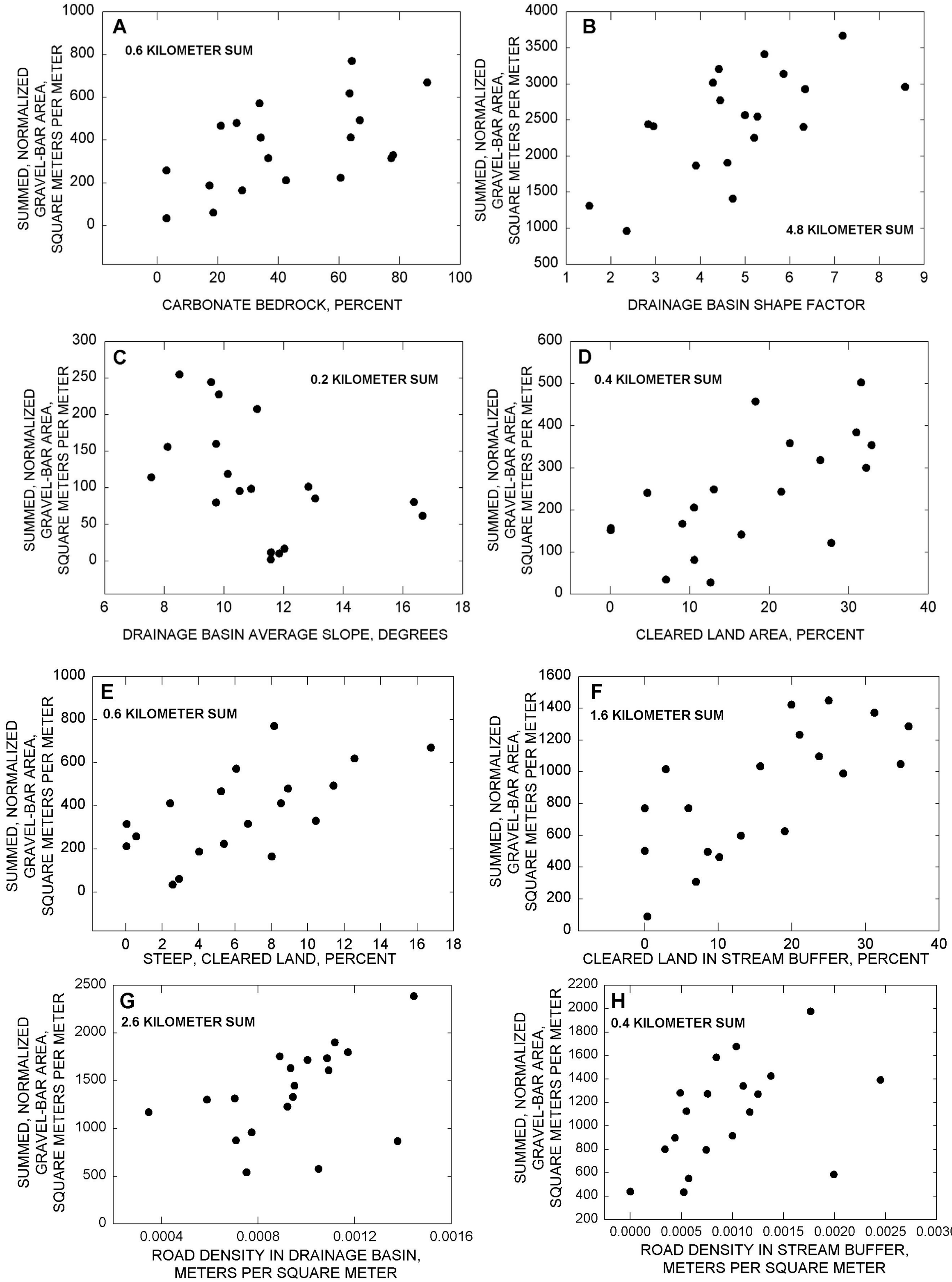



**Figure 48.** Selected scatter plots of drainage-basin characteristics and unit gravel-bar area inventories, Buffalo River. A. Unit gravel-bar area summed 0.6 km downstream plotted against percent carbonate bedrock in basin. B. Unit gravel-bar area summed 4.8 km downstream plotted against drainage-basin shape factor. C. Unit gravel-bar area summed 0.2 km downstream plotted against drainage-basin average slope. D. Unit gravel-bar area summed 0.4 km downstream plotted against cleared land area. E. Unit gravel-bar area summed 0.6 km downstream plotted against steep, cleared land area. F. Unit gravel-bar area summed 1.6 km downstream plotted against cleared land in stream buffers. G. Unit gravel-bar area summed 2.6 km downstream plotted against drainage-basin road density. H. Unit gravel-bar area summed 0.4 km downstream plotted against road density in stream buffer.

**Table 28.** Spearman rank correlation coefficients for Buffalo River gravel-bar area against drainage-basin variables

[km, kilometers; shaded values significant at p = 0.05; bold values > 0.5 or < -0.5]

| Variable | | Carbonate bedrock area | Drainage area | Drainage basin shape | Elevation range | Drainage basin average slope | Bluff area in stream buffer | Cleared land area | Steep, cleared land area | Cleared land in stream buffer | Road density | Road density in stream buffer |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Gravel-bar area summed at distances downstream | 0.2 km | 0.19 | 0.23 | -0.03 | -0.16 | **-0.63** | -0.38 | **0.54** | **0.52** | **0.54** | 0.07 | -0.01 |
| | 0.4 km | 0.39 | 0.22 | 0.07 | -0.12 | **-0.58** | -0.34 | **0.61** | **0.61** | **0.64** | 0.27 | 0.15 |
| | 0.6 km | **0.56** | 0.12 | 0.07 | -0.16 | **-0.51** | -0.38 | **0.61** | **0.65** | **0.60** | 0.40 | 0.35 |
| | 1.0 km | 0.35 | 0.23 | 0.08 | 0.09 | -0.29 | -0.31 | 0.42 | 0.45 | **0.58** | 0.33 | **0.52** |
| | 1.6 km | 0.19 | 0.43 | 0.17 | 0.17 | -0.30 | -0.16 | 0.44 | **0.52** | **0.71** | 0.29 | 0.45 |
| | 2.0 km | 0.32 | 0.29 | 0.28 | 0.09 | -0.25 | -0.20 | 0.43 | **0.52** | **0.67** | 0.46 | **0.53** |
| | 2.6 km | 0.15 | 0.36 | 0.44 | 0.28 | -0.07 | -0.02 | 0.31 | 0.31 | **0.62** | 0.49 | 0.49 |
| | 3.0 km | 0.15 | 0.40 | **0.52** | 0.21 | -0.26 | -0.16 | 0.47 | 0.42 | **0.70** | 0.47 | 0.39 |
| | 3.6 km | 0.08 | 0.31 | **0.54** | 0.19 | -0.05 | -0.04 | 0.24 | 0.17 | 0.49 | 0.31 | 0.35 |
| | 4.8 km | -0.03 | 0.23 | **0.56** | 0.11 | -0.15 | -0.12 | 0.25 | 0.10 | 0.39 | 0.14 | 0.11 |

enveloping relations between gravel-bar area and valley width, proximity of channel to valley wall, and channel sinuosity.

Tributary drainage-basin effects apparent in correlations and multiple regression models on the Buffalo River are most significant for gravel-bar areas summed 0-1.0 km downstream from the tributary junctions (tables 27, 28). For distances of 0-0.6 km, correlations with land-use variables are confounded by strong inverse correlations between land-use and slope, and an inverse correlation between slope and carbonate bedrock area. Hence, it is difficult to distinguish statistically the mechanism for increased gravel-bar areas: land use or natural increased gravel delivery due to carbonate bedrock. When gravel is summed for longer distances downstream, basin slope diminishes in significance in regression models, but the significance of cleared land in the stream buffer remains. At 3.0-3.6 km, basin shape is also significant in multiple regression models (table 27). Taken as a whole, these correlation models support the conclusion that on the Buffalo River gravel influxes from tributaries are presently closer to tributary junctions than on the Current River, and gravel-bar areas are significantly affected by either agricultural land use or geologic and physiographic differences between study drainage basins; these relations additionally are obscured over time as gravel is progressively transported downstream from tributary junctions.

## Conclusions

This study investigated links between drainage-basin characteristics and stream habitat conditions in tributaries of the Buffalo River, Arkansas and the Current River and Jacks Fork, Missouri. Data collected for tributary drainage basins, reach-scale channel characteristics, and main-stem gravel-bar area highlight the influence of physiographic controls on stream characteristics and suggest that land use exerts a subtle affect in these stream systems. Land-use effects were more prominent in the Buffalo River system than the Current River system.

GIS inventories of drainage-basin characteristics highlight the major physiographic and geologic differences between the two river systems. Buffalo River tributaries have more sandstone bedrock, steeper drainage-basin average slopes, greater elevation ranges, a greater proportion of streamside bluffs, and fewer impacts from karst hydrology than those in the Current River system. In both river systems, study drainage basins can be subset on the basis of differences in topography. In the Buffalo, differences in elevation range distinguish basins sourcing in the Boston Mountains from those sourcing in the Springfield and Salem Plateaus. In the Current, drainage-basin average slope separates the steep middle and east Current basins from the low-relief west Current basins.

Regression analysis of drainage-basin variables highlight the complex ways geology, physiography, and land use patterns are interrelated. For example, topographic relief variables are correlated with carbonate bedrock area, but with opposite trends in the two river systems. Drainage-basin average slope is negatively correlated with carbonate bedrock area in the Buffalo River system and positively correlated in the Current River system. Stratigraphic position and erosional history appear to moderate the effect of lithology on topography. Impacts from land use may also differ in the two river systems. Although cleared land area is negatively correlated with drainage-basin average slope in both river systems, basins in the Buffalo tend to have more cleared land for a given average slope than those in the Current. This suggests that the impact from land use may be greater in the Buffalo River system where more cleared land is in sensitive landscape positions.

Analyses of reach-scale channel characteristics suggest that physiography is the primary control on channel characteristics. After accounting for differences in drainage area, channel geometry and substrate variables are positively correlated with measures of topographic relief or an indicator variable specifying river system. Buffalo River tributaries tend to have larger bankfull and residual pool dimensions and coarser substrate than those in the carbonate-dominated Current River system. These differences are consistent with flashy runoff and large storm flows in the rugged Buffalo River system and with impacts from the karst hydrology in the Current River system.

When basins are subset by river system, Current River tributaries continue to show associations consistent with impacts from karst hydrology. Tributaries that drain the karst-rich western Current have smaller channel dimensions and finer and more embedded substrate than those that drain the middle and eastern part of the basin. West Current drainage basins also show some indication of impacts from land use – cleared land area in these basins is negatively correlated with the proportion of residual pools and positively correlated with embedded substrate.

When Buffalo River tributaries are subset, channel characteristics show strong associations with geology and land use. Drainage basins with larger proportions of carbonate bedrock and cleared land have shallower channels, a lower proportion of residual pools, better-sorted, gravel-rich substrate, and more eroding banks than those with little cleared land and abundant sandstone bedrock. Because carbonate bedrock and cleared land area are correlated, it is difficult to separate associations between natural and anthropogenic factors.

Measurements of gravel-bar area on main-stem rivers are consistent with basin-scale and reach-scale findings. After accounting for differences due to valley morphology, gravel-bar area within 1 km of tributary junctions on the Buffalo River show associations with tributary geology, physiography, and land use. Gravel-bar area is positively correlated with carbonate bedrock and cleared land area and negatively correlated with drainage-basin average slope. These correlations diminish as gravel-bar area is measured over longer distances downstream.

In contrast, on the Current River, correlations between gravel-bar area and tributary characteristics are strongest when measured over greater distances downstream. Gravel-bar areas summed over 3.0-4.8 km downstream from the tributary confluences is positively correlated with drainage-basin average slope and negatively correlated with cleared land area. This difference is consistent with the distinction between west and middle and east Current groups – eastern basins have steeper slopes, little cleared land area, and fewer impacts from karst hydrology than west Current drainage basins. Steeper slopes and a higher relative transport capacity may facilitate gravel transport out of these basins compared to the karst-rich west Current basins. Gravel-bar distributions along the Current River are also more consistent with hypothesized, lagged historical effects than with recent impacts from land use. Temporal comparisons of 1992 and 1996 gravel distributions show downstream translation of gravel that is consistent with time-series models of impacts from low-level historical disturbance.

This study highlights the relation between landscape physiographic characteristics and stream conditions in the Ozark Highlands. Channel dimensions, habitat distributions, and substrate characteristics are related to drainage-basin geology, size, and physiographic relief. The influence of these natural landscape characteristics appears to overshadow relations between rural land use and stream physical habitat conditions in the study basins. For the Buffalo and Current River systems, land use appears to exert a subtle influence notable only when streams are subset into physiographic groups.

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# Appendices

## Appendix 1

Estimates of land cover in this study were based on a preliminary version of National Land Cover Data (NLCD) developed by the U.S. Geological Survey's Eros Data Center (http://edcsgs9.cr.usgs.gov/programs/lccp/nationallandcover.html ). Eros released preliminary versions of the coverage for Missouri and Arkansas in July and August 2000. It was created from Landsat Thematic Mapper Images collected during the late 1980's and early 1990's and maps 21 classes of ground cover with a grid cell size of 30-meters. The data set is particularly valuable for this project, because data classes and processing techniques were uniform across state boundaries.

Until this data set became available, earlier projects in the parks relied on land cover data sets developed by state or university researchers. These coverages include:

- 1992 Land Cover for the State of Missouri developed by the Missouri Resource Assessment Partnership, version 2.3 (MoRAP, 2000; http://www.cerc.cr.usgs.gov/morap/projects/lulc/landcover2.htm ).
- 1992 Land Cover for the Buffalo Watershed developed by the University of Arkansas (Scott and Hofer, 1995).
- 1992 Land Cover for the State of Arkansas developed by the University of Arkansas (CAST, 1997; http://cast.cast.uark.edu/local/isite/GeoLibraryCatalog.htm#Themes).

These three coverages are also based on Landsat Thematic Mapper images from the early 1990's, yet because their processing methods and land cover classes were different, it is difficult to compare land cover between the Buffalo and Current study basins.

The NLCD data set also provided an opportunity to compare different land cover versions. Some error is inherent in all classification methods, but without extensive "ground truthing" the magnitude of error is difficult to quantify. In general, there was good agreement between the NLCD and MoRAP land cover versions, the two coverages available for the Current River drainage basin. The average difference of cleared land (dominantly pasture) in a tributary study basin was 1.6% and the maximum difference was 4.2% with MoRAP's coverage documenting slightly more cleared land than the NLCD coverage. For the Buffalo drainage basin, the NLCD and CAST land cover version were also similar – the average difference in cleared land area for tributary study basins was 2.2% and the maximum different was 5.4%. Depending on the drainage basin, the CAST landcover version either underestimated or overestimated cleared land area. There was a more substantial difference between the land cover developed by Scott and Hofer (1995) and the NLCD data set. The Scott and Hofer (1995) coverage consistently mapped a greater proportion of cleared land with an average difference compared to the NLCD coverage of 10% and a maximum difference of 18%. Tomahawk Creek, for example, was mapped with 49% cleared land area (pasture and grasslands) by the Scott coverage but only 33% by the NLCD coverage. The difference between the NLCD and Scott and Hofer (1995) land cover versions accounts for discrepancies between the proportion of cleared land reported in this study and in earlier Buffalo River drainage-basin studies.

## Appendix 2

## Detailed procedure for reach-scale channel surveys [designed for a field team of three]:

1. [**Entire Team**] Identify the downstream riffle for the reach, close to the confluence for the mainstem river but upstream of backwater effects. Flag it and take a Global Positioning System (GPS) reading. Walk upstream through four riffles; identify potential instrument positions for surveying. Record a GPS reading at the top of the fourth riffle; this will mark the top of the longitudinal profile. The number of riffles within a reach may vary slightly, be sure to include a distance equal to at least 15-20 channel widths.

2. [**Persons 1 and 2**] Survey points along the thalweg of the channel spacing them as needed to define the topography (about 3-10 meters apart). Two points will be shot at each location, the first point with base of pole on ground, the second with the base of the pole on the water surface. For the ground point, use data logger codes to note:
   a. habitat type
   b. dominant substrate size
   c. the proportion of embeddedness

   For water surface point use data logger codes to note:
   a. the proportion of the left bank covered with vegetation – this is an estimate of vegetation cover on vertical or near vertical banks below the bankfull elevation, do not consider point bars
   b. erosion on the left bank – Descriptive classes are “not eroding, moderately eroding, or severely eroding”. Moderately eroding banks show limited root exposure or a small portion of the bank undercut; severely eroding show near-vertical cut banks with many exposed roots.
   c. the proportion of the right bank covered with vegetation
   d. erosion on the right bank

3. [**Persons 1 and 2**] Where apparent, survey indicators of bankfull elevation. Note the quality of the indicator in the data logger. We found indicators on point bars to be especially consistent.

4. [**Person 3**] Take photographs of gravel-bar substrate at locations equally spaced across the point bar along a line bisecting the adjacent riffle. Place label with site name and bar number in corner of photo frame. Record photo numbers on data sheet.

5. [**Person 3**] Decide on locations for cross-sections within each of three glides. Stretch tag lines across cross section. While choosing cross-section locations, take photographs of the study reach looking upstream and downstream. Fill out top of data sheet and sketch reach and make notes as needed.

6. [**Person 3**] Conduct embeddedness measure at locations one third and two thirds across the wetted width of each glide cross section. Place sediment viewer to break water surface and estimate the proportion of fines covering the 60x60 cm area of viewer frame. Refer to illustration cards to help with making visual estimates. Record estimates on data sheet.

7. [**Person 1 and 2**] Survey cross sections where Person 3 has set up the tag line. Survey estimates of bankfull maximum and minimum elevations. Estimates of bankfull elevation will be plotted and compared with other estimates made along the longitudinal profile. At each point, record substrate.

8. [**Person 3**] Conduct canopy closure measure at the water’s edge of each cross section. Hold the densiometer on the transect line perpendicular to the bank 30 cm from and 30 cm above the shoreline. Count the number of intersections within the taped V that reflect vegetation. Record this number (out of a total of 17) on the data sheet. This procedure is described more completely in Fitzpatrick and others (1998).

## **Appendix 2** continued

9. [**Persons 1, 2, and 3**] Repeat steps 5-7 until all cross-sections have been surveyed.

10. [**Persons 1, 2, and 3**] Conduct pebble counts in three glide habitats along the surveyed cross section. Use data sheet to record particle size. Scatter points throughout glide picking up the first particle reached on each "blind" touch to the streambed.

Table of codes used for data entry into data logger

| Habitat | Code | Substrate | Code | Other Observations | Code |
|---|---|---|---|---|---|
| Bedrock riffle | 1 | Bedrock | 11 | Embeddness | % in intervals of 10 |
| Alluvial riffle | 2 | Mud/organics | 12 | | |
| | S= step | Sand | 13 | LB Veg % | % in intervals of 10 |
| Glide (run) | 3 | Fine/Medium Gravel (2-16mm) | 14 | LB eroding? | Y = severely<br>M = moderately<br>N = no |
| Race | 4 | C. Gravel (16-32mm) | 15 | RB Veg % | % in intervals of 10 |
| Obstruction Pool | 5 | Very Coarse Gravel (32-64mm) | 16 | LB eroding? | Y = severely<br>M = moderately<br>N = no |
| Lateral Pool | 6 | Small Cobbles (64-128mm) | 17 | | |
| Bluff Pool | 7 | Lg Cobbles (128-256mm) | 18 | Bankfull Indicators | BF1 = good quality |
| Mid-Channel Pool | 8 | Sm Boulders (256-512mm) | 19 | | BF2 = fair quality |
| | | Lg Boulders (>512 mm) | 20 | | BF3 = poor quality |

**Appendix 2** continued

Tributary: ___________________________ Date and Time: __________________

GPS upstm: ___________ E ____________ N +/- ____ elev_______ Weather: _______________________

GPS dnstm: ___________ E ____________ N +/- ____ elev_______ Data Logger File Name: __________

Flood plain Vegetation: ____________________________________ Team: ______________________

**Draw sketch of reach on back of page and make notes.** Reach Photo Numbers:___________

**Photo Sieving:** (photo number) (on cross-section at middle of framework riffles)

| | **Bar 1** | | **Bar 2** | | **Bar 3** | |
|---|---|---|---|---|---|---|
| | A | B | A | B | A | B |
| Surface | | | | | | |

**Glide Embeddedness and Canopy Closure**:

| | **Glide 1** | | **Glide 2** | | **Glide 3** | |
|---|---|---|---|---|---|---|
| | LB | RB | LB | RB | LB | RB |
| % embedded | | | | | | |
| # crosses covered | | | | | | |

**Glide Pebble Count:** (particles <4 mm recorded as 4)

| **Glide 1** | | | | **Glide 2** | | | | **Glide 3** | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
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U.S. Department of the Interior
U.S. Geological Survey

As the Nation's principal conservation agency, the Department of the Interior has responsibility for most of our nationally owned public lands and natural resources. This responsibility includes fostering the sound use of our lands and water resource; protecting our fish, wildlife, and biological diversity; preserving the environmental and cultural values of our national parks and historical places; and providing for the enjoyment of life through outdoor recreation. The Department assesses our energy and mineral resources and works to ensure that their development is in the best interests of all our people by encouraging stewardship and citizen participation in their care. The Department also has a major responsibility for American Indian reservation communities.

U.S. DEPARTMENT OF THE INTERIOR
March 3, 1849

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