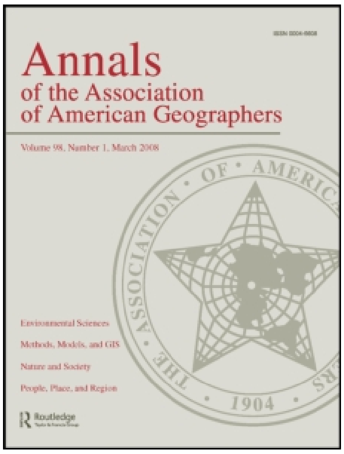

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Spatial and Temporal Patterns of Stream Channel Incision in the Loess Region of the Missouri River

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Stream channel incision is severe in the loess-dominated region of western Iowa and eastern Nebraska, with recent incision related to sediment capture by reservoirs on the Missouri River. This study confirms that the temporal pattern of incision follows the rate law proposed by Graf (1977) with half-lives ranging from two to nine years and stream channels throughout the affected watersheds approaching a new dynamic equilibrium in one to three decades. The resulting spatial pattern of incision on tributaries is demonstrated to follow a simple rule of base-level lowering at the outlet multiplied by a flow-length ratio ($R^2 = 0.71$). This rule is used to estimate depth of channel incision along all tributary streams of the Nebraska reach of the Missouri River and confirms that Missouri River degradation, along with other local disturbances such as channelization, is an important cause of tributary stream incision in the study area. Using the flow-length ratio rule, a spatial model of stream channel incision is developed that accounts for influences of channelization, grade controls, the erodability of geologic materials, and time. *Key Words: base level, flow-length ratio, fluvial geomorphology, map algebra, stream channel incision.*

河道侵蚀在爱荷华州西部和内布拉斯加州东部以黄土为主的地区是非常严重的，最近的侵蚀与密苏里河水库的泥沙捕获有关。这项研究证实，侵蚀时间模式符合格拉夫（1977年）提出的侵蚀率法，其半衰期为2至9年，在10年到30年的时间内，流经的河道影响整个流域，达到一个新的动态平衡。由此产生的侵蚀支流的空间格局遵循一个简单的规则：基准面在出口处的降低乘以流动长度比（R^2 = 0.71）。这条规则用来估计汇流到密苏里河的内布拉斯加州各条支流的河道切口深度，并且确认密苏里河的退化以及其他的地方干扰，例如通渠，是导致研究区支流切口的一个重要原因。使用流动长度比规则，一个考虑渠道化，分级控制，地质材料的侵蚀率，和时间影响的河道切口的空间模型得以建立。*关键词：基准面，流动长度比，河流地貌，地图代数，河道切口。*

La incisión del canal de corrientes es severa en la región con cobertura de loess en el occidente de Iowa y oriente de Nebraska, donde la incisión reciente está relacionada con la captura de sedimentos por los reservorios del Río Missouri. Este estudio confirma que el patrón temporal de incisión está de acuerdo con la ley propuesta por Graf (1977), patrón caracterizado por vidas medias que varían de dos a nueve años y por canales que a través de toda la cuenca afectada se aproximan a un nuevo equilibrio dinámico entre una y tres décadas. Se demuestra que el patrón espacial resultante de incisión en los tributarios sigue una simple regla de descenso del nivel de base a la salida, multiplicado por una razón flujo-longitud (R^2 = 0.71). Esta regla se utiliza para estimar la profundidad de incisión del canal a los largo de todas las corrientes de Nebraska tributarias del Río Missouri y confirma que la degradación de este río, junto con otras perturbaciones locales, como canalización, son causas importantes de incisión de corrientes tributarias en el área de estudio. Usando la regla de la razón fujo-longitud, se desarrolló un modelo espacial de incisión del canal de corrientes que toma en cuenta las influencias de canalización, controles de grado, la erosionabilidad de materiales geológicos y el tiempo. *Palabras clave: nivel de base, razón fujo-longitud, geomorfología fluvial, álgebra de mapas, incisión de canal de corriente.*

Alluvial stream channels adjust to changes in discharge, slope, and sediment supply through channel bed aggradation or degradation (Lane 1955). Channel incision can occur as a response to increases in stream power (Simon 1992), decreases in sediment supply, increases in steam gradient, or a lowering of base level. In the case of base level, incision begins at the site of base-level lowering and migrates progressively upstream until attenuated by less erodible material or reduced stream power. These dynamics have been described in theory (Mackin 1948; Lane 1955; Galay 1983), studied experimentally in flumes (Shepherd and Schumm 1974; Holland and Pickup 1976; Gardner 1983) and in rainfall erosion facilities

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(McLane 1978), numerically simulated (Begin, Meyer, and Schumm 1981; Slingerland and Snow 1988), and qualitatively assessed in the field through channel evolution models (Simon and Hupp 1986; M. J. Daniels 2002).

The temporal and spatial patterns of stream channel incision at watershed scales, however, are less well understood. Using data from stream cross sections on tributaries of the Missouri River in eastern Nebraska and western Iowa, this study examines the rate of channel incision and develops, tests, and applies a model describing the temporal and spatial distribution of channel incision resulting from sediment capture and a lowering of base level. Streams in this area have been subjected to widespread base-level lowering as a result of degradation of the Missouri River and channelization. These streams isolate the causes of down cutting because (1) the study area is underlain predominantly by erodable loess, (2) stream adjustment to base-level lowering is rapid, (3) most determinants of base-level lowering are identifiable in both time and space, and (4) independent variables such as slope and land use can be controlled statistically. The study area possesses an extensive historical record of streambed elevations in the form of hundreds of bridge cross sections along fifteen Missouri River tributaries (U.S. Army Corps of Engineers 1987, 1991; Rus, Dietsch, and Simon 2003). The Nebraska reach of the Missouri River basin thus serves as an experimental site in which to test temporal models of stream incision and to develop a spatial model of stream incision at watershed scales.

Causes and Effects of Stream Channel Incision

Over geologic time scales, drainage networks develop through sustained channel bed incision. Numerous examples of accelerated bed degradation (Erskine 1999) can be found from nearly every continent, however (e.g., Lane 1934, 1955; Stanley 1951; Lane and Borland 1954; Taylor 1978; Williams and Wolman 1984; Pinter, van der Ploeg, Schweigert, and Hoefer 2006), resulting in dramatically increased sediment loads; reduced water quality; lowering of riparian water tables; and damage to infrastructure such as bridges, pipelines, water intakes, marinas, and harbors (Lane 1955; Leclerc, MacArthur, and Galay 1997; Lohnes 1997). In Iowa, damages to infrastructure caused by channel incision since 1900 have been estimated at over $1 billion (Hadish et al. 1994). Channel and water quality changes can further lead to a reduction in aquatic habitat and loss of riparian biological diversity (James 1991; Shields, Knight, and Cooper 1994; Thorne 1999).

Unlike temporary scour and fill, channel incision systematically lowers the channel bed by erosion (Figure 1) when stream power produces shear stresses exceeding the cohesion of geologic substrates. This excess stream power can be caused by enhanced channel slope, reduced sediment loads, or increases in channel bed abrasion relative to alluvial thickness (Stock and Montgomery 1999; Sklar and Dietrich 2000). Incision occurs either due to upstream factors that propagate incision downstream or to downstream factors that propagate incision upstream. Increases in the water

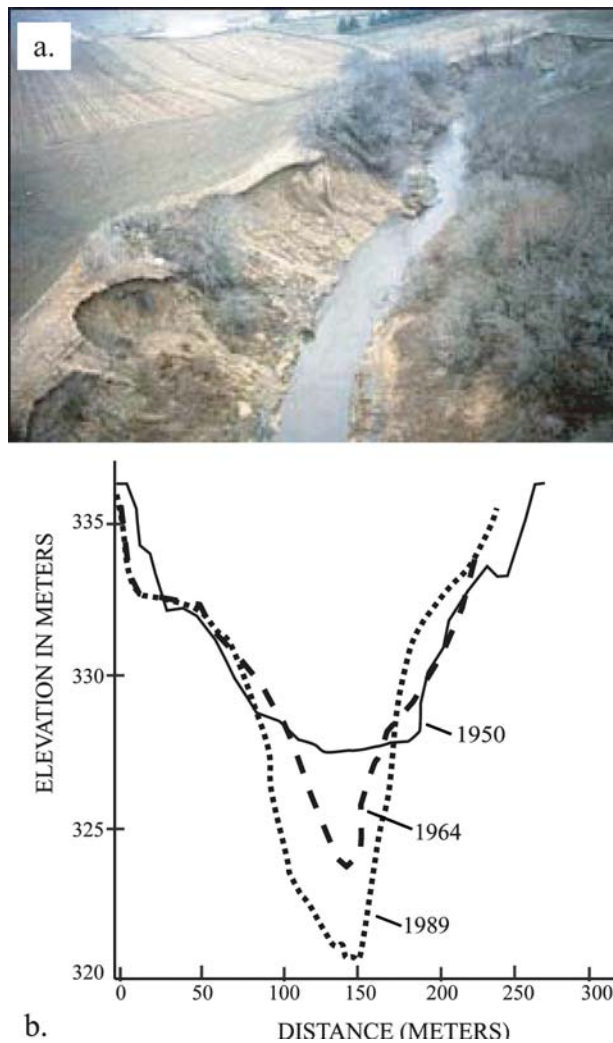

Figure 1. (A) Typical condition of stream channels in the loess area of eastern Nebraska and western Iowa. Many signs of recent degradation are identifiable in this photograph, including the near-vertical banks, evidence of bank slumping, and exposed roots. (B) Changes in a corresponding channel cross section, 1950–1989.

discharge or slope, or decreases in the sediment load or mean particle size, often induced by changes in upstream land use or by sediment storage following dam construction (e.g., Stanley 1951; Leopold, Wolman, and Miller 1964; Petts 1977; Kellerhals 1982; Williams and Wolman 1984; Brandt 2000), can initiate channel incision.

Channel incision caused by an increase in gradient, often with rapid upstream progression along a *knickpoint* (a convex-upward inflection point in the longitudinal profile of a stream channel), results from a shortening of the channel through channelization or meander cutoffs or by the lowering of the local base level. The process continues up primary streams and their tributaries until the drainage network has adjusted to a lower equilibrium elevation. The rate of headward advance depends on the alluvial properties and basin physiographic, geomorphic, and hydrologic characteristics. Studies of channel incision have examined semiarid arroyos (Schumm 1961; Leopold, Emmitt, and Myrick 1966; Melde and Scott 1977; Patton and Schumm 1981; Balling and Wells 1990) and gully development related to changes in land use (Ireland and Sharp 1939) or climate (Graf 1977). Other studies examined incision in response to channelization and base-level lowering induced by land use change (R. B. Daniels 1960, 1966; Pickup 1977; James 1991; M. J. Daniels 2002), in response to structural controls (Morisawa 1968), upstream of meander cutoffs (Lane 1955; M. J. Daniels 2002), and in flume studies (Holland and Pickup 1976; Gardner 1983).

Of particular interest to this study are the streambed adjustment models in Lane (1955) and flume experiments performed by Brush and Wolman (1960). Lane (1955) describes a similar channel response to base-level lowering, meander cutoffs, or channelization, with an upstream-migrating knickpoint and an exponentially decreasing rate of channel incision (Figure 2). In their flume studies, Brush and Wolman (1960) found that knickpoint development following base-level lowering first follows the main trunk stream and then works upstream into tributaries. In their experiment using uniform unconsolidated sand and silt, the degree of incision decreased upstream into the drainage network in a uniform manner as a function of distance upstream from the point of base-level lowering. Simon (1992) also found this pattern in the low-gradient Obion-Forked Deer River system of incising channels in west Tennessee. Flume experiments (Schumm and Parker 1973) and field studies (Petts 1979, 1980; Rinaldi and Simon 1998), however, describe how a "complex response"

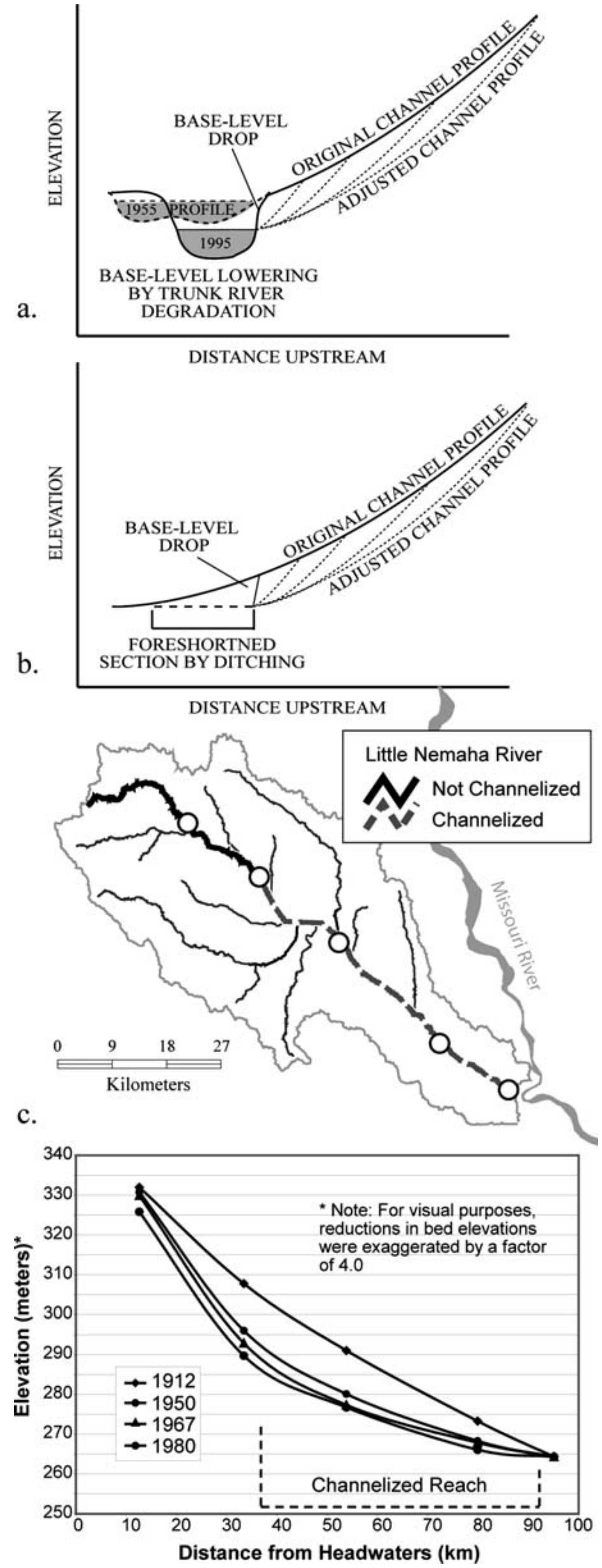

Figure 2. Similar theoretical channel responses to (A) base-level lowering or (B) meander cutoffs or channelization. This response is shown to occur in the Little Nemaha River (C) where 55 km were channelized in the early twentieth century, leading to channel degradation within the ditched reach and base-level lowering for points upstream and for tributaries to the Little Nemaha River.

can occur following a reduction in base level through sediment delivery feedbacks and downstream aggradation. In contrast, Schumm, Mosley, and Weaver (1987) found that the rate of incision simply declines exponentially over time following base-level lowering. Similarly, Graf (1977) presents a straightforward model of the headward advance of gullies in response to increases in summer rainfall intensity where, after a brief reaction time, gully advance is at first rapid and then decays exponentially, asymptotically approaching a new dynamic equilibrium. Simon (1992) shows that these geomorphic responses are consistent with the system's tendency to minimize the rate of energy dissipation with time.

Most channel incision studies focus on modeling the physical processes at work at the channel bed and banks, including shear stresses and stream power. These approaches require a great deal of site-specific data. Researchers have tended to deal with the data demands by limiting the spatial or temporal scope of the analysis (Pickup 1977; Begin, Meyer, and Schumm 1981; Schumm, Harvey, and Watson 1984; Simon and Hupp 1986). Few studies examine the spatial pattern of channel incision at watershed scales. One study conducted with limited data established that, following construction of Bagnell Dam, the Osage River in the Missouri Ozarks incised with degradation proceeding downstream along the Osage, lowering base level for tributaries downstream of the dam (Germanoski and Ritter 1988). These tributaries then similarly incised, with knickpoints propagating upstream until constrained by root armoring, with periodic collapsing allowing knickpoints to migrate farther upstream. In a more detailed study, Simon and Rinaldi (2006) strongly confirmed the Graf (1977) rate law model for stream channel incision over time on channelized streams as well as below dams. Their seven-stage model of channel response to disturbances that result in a surplus of sediment transporting power relative to sediment supply includes rapidly migrating knickpoints and a progression from headwater channels in early phases of adjustment progressing to latter stages of adjustment in downstream reaches.

Using cross-sectional data from the loess region of the Missouri River, this article addresses three research questions: (1) What is the temporal pattern and rate of stream channel incision in loess-derived silt following a lowering of base level or reduction in sediment supply? (2) What is the resulting spatial pattern of channel incision at a watershed scale? (3) Can a watershed-scale spatial and temporal model of stream incision be derived?

Methods

The Study Area

The area of investigation consists of the loess-dominated watersheds tributary to the Missouri River between Gavins Point Dam (River Mile 811) and the Nebraska–Kansas state line (River Mile 490; Figure 3). This area was chosen because it has (1) a relatively uniform geologic setting consisting primarily of erodable loess-derived alluvial materials, (2) a well-documented historical record of stream modifications for the Missouri River and tributary streams, and (3) numerous repeat cross-sectional measurements at stream sites that document stream incision over space and time.

The 43,000 km^2 study area lies in the Dissected Till Plains of the Central Lowlands physiographic province (Fenneman 1946). The underlying glacial till is covered by some of the thickest (5–25 m) Pleistocene loess deposits in North America (Luttenegger 1987). Because of the loess mantle on the uplands, the region is described as highly erodable by the Soil Conservation Service (1981). Alluvial soils and stream beds and banks consist primarily of loess-derived silt, silty-clay loam, and loamy silt (Rus, Dietsch, and Simon 2003).

The reach of the Missouri River that forms the eastern border of Nebraska has been altered by human activities that have narrowed and deepened the river and thereby lowered base level for tributary streams. Six large dams were constructed upstream by the U.S. Army Corps of Engineers between 1937 and 1963 for flood control, power production, irrigation, water supply, releases of water for navigation, recreation, and fish and wildlife (Figure 3). The reservoirs flood over 400,000 hectares, contain 92 billion m^3 of storage space, and extend 1,200 km, leaving only 525 km of flowing river between the reservoirs. Below the most downstream of these dams (Gavins Point), the Missouri River flows 1,300 km to the confluence with the Mississippi River. Prior to dam construction and reservoir sedimentation, an annual average of 135 billion tonnes of sediment was transported by the river (Mellema and Wei 1978). In particular, the closure of Fort Randall and Garrison Dam in 1954 and Gavins Point Dam in 1955 corresponded with a dramatic drop in sediment load 310 km downstream at Omaha (Figure 4). In addition to the greatly reduced sediment supply, much of this reach of the Missouri River has been altered to accommodate barge navigation. Wing dams have been installed downstream of Nebraska's Ponka State Park (River Mile 754, Figure 3) to maintain navigable depths of 2.7 m.

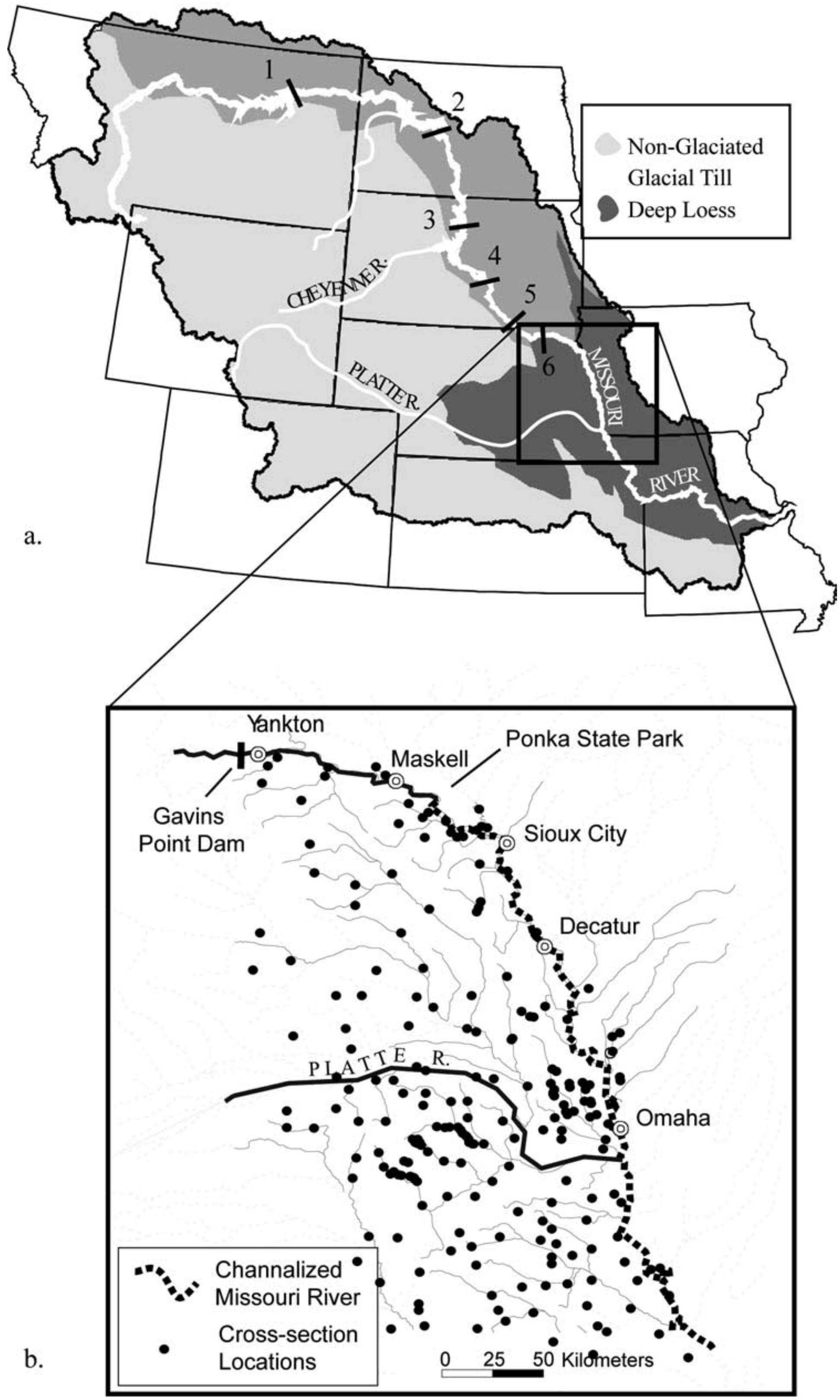

Figure 3. (A) The Missouri River basin showing regions of glacial till, loess, and nonglaciated regions as well as the six mainstem Missouri River dams: (1) Fort Peck, (2) Garrison, (3) Oahe, (4) Big Ben, (5) Fort Randall, and (6) Gavins Point. (B) The location of the five Missouri River gages (Yankton, Maskell, Sioux City, Decatur, Omaha) and tributary sites used for model calibration in this study.

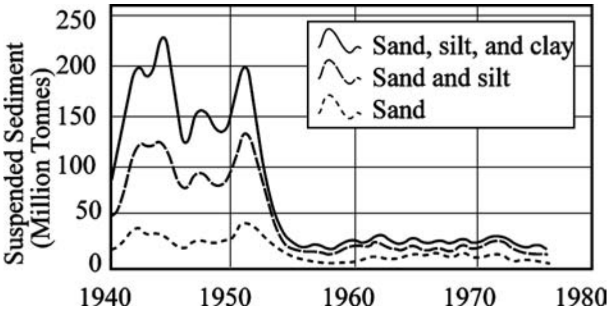

Figure 4. Annual sediment loads for the period 1940 to 1977 at Omaha, Nebraska, 310 km downstream from Gavins Point Dam (based on data from U.S. Army Corps of Engineers 1991). The great reduction in sediment load coincides with the closure of Fort Randall and Garrison Dam in 1954 and Gavins Point Dam in 1955.

The reach below Ponka has thus been transformed from a complex multichannel system into a much more uniform, single-thread channel (Figure 5) with greater depth and narrower width (Branyan 1974; Hallberg, Harbaugh, and Witinok 1979; Schumm, Harvey, and Watson 1984; Lohnes 1997).

Severe channel incision has been documented in the loess region streams tributary to the Missouri River since the early 1900s. Researchers have used examples from this region to describe erosional processes (R. B. Daniels 1960; Brice 1966; R. B. Daniels and Jordan 1966), channel widening (Lohnes 1997; Bravard, Kondolf, and Piegay 1999), channel evolution (Hadish et al. 1994; Simon and Rinaldi 2000), channel stabilization (Lohnes 1997), and the effect of human alterations to stream channels (Ruhe and Daniels 1965; U.S. Army Corps of Engineers 1991; Simon 1994; Schneiders 1996; Simon and Rinaldi 2000). Causes of historic incision include (1) nineteenth-century land clearing and poor soil conservation practices (Simon and Rinaldi 2000), (2) channelization completed primarily in the early twentieth century (Simon and Rinaldi 2000, 2006; Rus, Dietsch, and

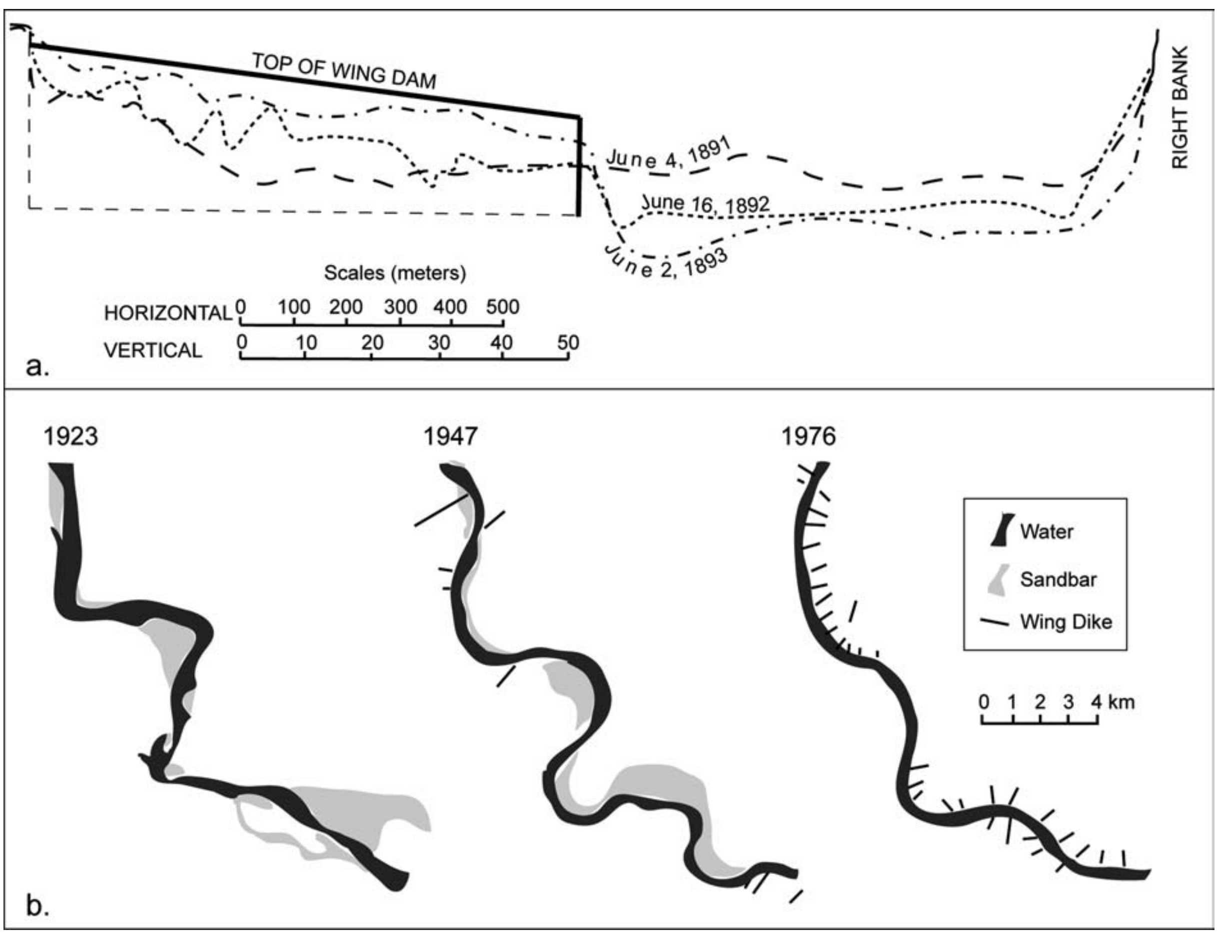

Figure 5. (A) This example of the effect of a wing dam (dike) constructed in August 1891 near the mouth of the Osage River on the cross section of the Missouri River shows how the dike narrowed and deepened the channel over a period of two years (based on U.S. War Department 1885). (B) Changes in the water-surface area (dark gray) and sandbar area (light gray) of the Missouri River, Monona County, Iowa, 1923 to 1976, as the result of a dike field (after Hallberg, Harbaugh, and Witinok 1979).

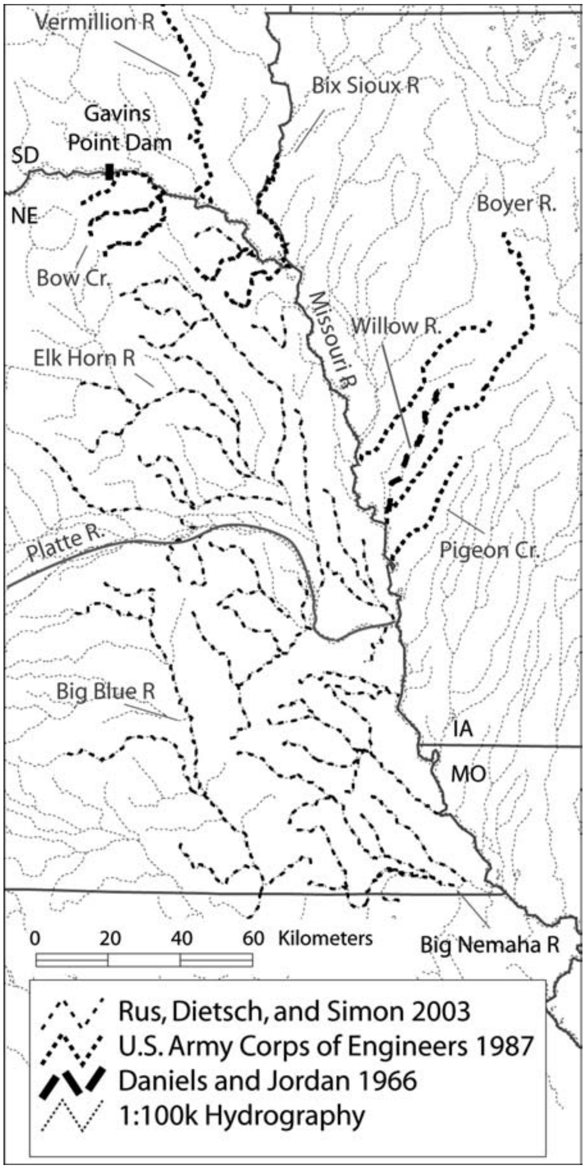

Figure 6. Stream segments tributary to the Nebraska reach of the Missouri River with documented incision histories.

Simon 2003; Figure 6), (3) long-term geologic processes, (4) changes in climate (R. B. Daniels and Jordan 1966; Bettis 1990), and (5) tributary incision caused by the degradation of the Missouri River (U.S. Army Corps of Engineers 1991; Schneiders 1996; National Research Council 2002; Rus, Dietsch, and Simon 2003). The net result is a severely eroded landscape in which streams have degraded by as much as eight meters over the past hundred years (U.S. Army Corps of Engineers 1991; Rus, Dietsch, and Simon 2003).

Data Sources and Site Selection

Measurements documenting changes in streambed elevations were assembled for the Nebraska reach of the Missouri River (U.S. Army Corps of Engineers 1991, 1996; U.S. Army Corps of Engineers-RCC 1998; Figure 7) and for sites along 128 tributary stream segments (R. B. Daniels and Jordan 1966; U.S. Army Corps of Engineers 1987; Rus, Dietsch, and Simon 2003; Figure 8). The Missouri River data come from gaging station records and bathymetric surveys. Tributary cross-sectional data were originally obtained from hydrographic survey records, U.S. Geological Survey stream gage records, and bridge design and maintenance records. Using these six sources, we amassed a database containing 324 cross sections over time for the Nebraska reach of the Missouri River and 208 cross-section sites along tributaries.

From the cross-section sites, different sites were selected for various components of this study including: (1) determining locations and depth of base-level lowering; (2) analysis of temporal trends and rates of incision; (3) calibrating the relationship among depth of incision, base-level lowering, and basin parameters over space; and (4) determining the effects of channelization and grade controls on incision (Figure 8). To establish points of base-level lowering, all forty sites located downstream of other cross-section points with a similar period of record were selected. To assess the rate of response to disturbance, all thirty-six sites were selected that had multiple cross-sectional measurements over the period of incision. To assess spatial patterns, all sixty-three sites upstream of sites with established base-level lowering or upstream of the confluence with a degraded reach of the Missouri River were selected. To establish spatial patterns, two regressions were performed, first excluding sixteen sites containing known channelized reaches and grade controls to isolate overall spatial patterns, then reintroducing them to determine the effects of channelized reaches and grade control on channel incision. A catalog of gage sites, characteristics, and role in these analyses is available at http://www.augustana.edu/users/ggheine/incision_proj.htm.

In addition to the cross-section measurement sites, water surface elevation trends were quantified along the length of the Nebraska reach of the Missouri River. In the same manner that sea level controls base level for rivers draining to the ocean, the water surface of the Missouri River sets base level for its tributaries. Missouri River water-surface elevation trends have been

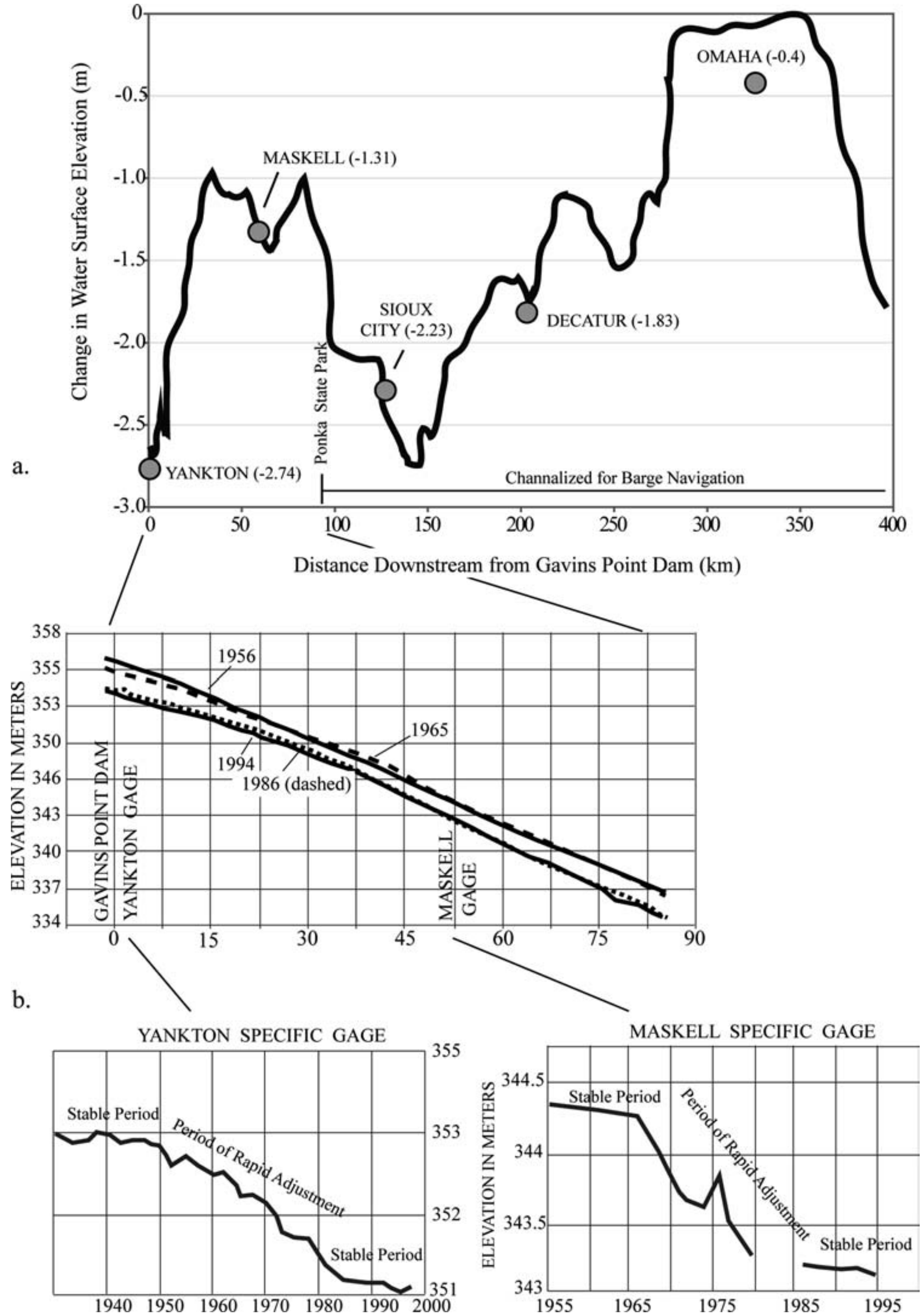

Figure 7. (A) Missouri River water-surface elevation change from 1957 to 1991 at 849 cms (30,000 cfs) with gage locations based on data from U.S. Army Corps of Engineers (1991). Stage change determined by specific gage analysis is indicated for each gage in parentheses. (B) Missouri River water-surface elevation change profiles for 1956, 1965, 1986, and 1994 below Gavins Point Dam based on data from the U.S. Army Corps of Engineers (1996) and trends for specific gages at Yankton and Maskell. The correlation between profile-derived and specific-gage-derived data is 0.98; the slightly different estimates are evident at the Omaha gage.

quantified along the Missouri River by (1) using historic data at rated gaging sites (U.S. Army Corps of Engineers-RCC 1998; Chen, Rus, and Stanton 1999; Pinter, Wlosinski, and Heine 2002; Pinter and Heine 2005) and (2) using existing hydraulic model results performed by the U.S. Army Corps of Engineers (1987, 1991, 1996). A 1991 study used two sets of channel cross sections (measured in 1957 and 1991) to

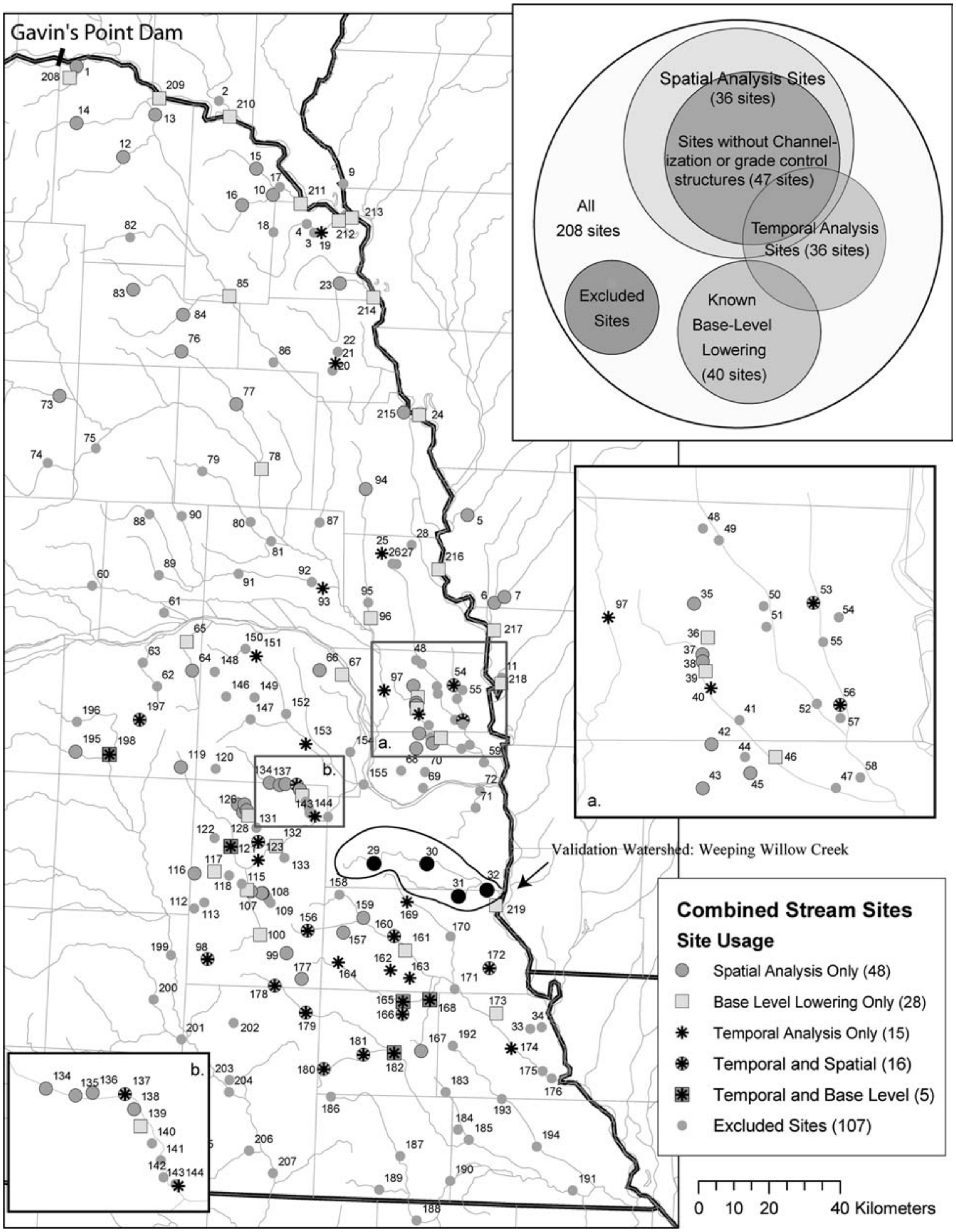

Figure 8. (A) Venn diagram showing criteria for selection of cross-section sites in different components of this study: (1) All 208 sites from U.S. Army Corps of Engineers (1987) and Rus, Dietsch, and Simon (2003); (2) 63 sites used to calibrate regression model; (3) 47 sites used to calibrate flow-length ratio; (4) 36 sites used to calibrate rate law analysis; (5) 40 sites used to establish base-level for upstream calibration sites; and (6) excluded due to insufficient number of cross sections in relevant time period. (B) Location of cross sections for these components of the study.

hydraulically model the water surface elevations associated with the median discharge of 849 cms. The total reduction in streambed elevation over this period shows degradation (1) immediately downstream of Gavins Point Dam; (2) near Sioux City, Iowa, where wing dams have been constructed; and (3) along the Nebraska–Missouri reach, where meander cutoffs were constructed. The streambed is more stable near Omaha, Nebraska, where the Platte River delivers a large influx of sediment (Figure 7A). Using hydraulic modeling and historic channel cross sections, a 1996 Corps study modeled the water-surface elevation at four time steps (1956, 1965, 1986, 1994) between Gavins Point Dam and Ponka State Park (Figure 7B).

Because data were obtained from a variety of sources, several different sources of uncertainty were introduced. These uncertainties were a result of differences in methods of data collection, locations, and dates the data were collected. For example, most of the streambed-elevation sites were located at bridge crossings. Although bridges are known to cause local scour, their construction and maintenance records provide the only historical record of channel change on many small rivers and streams. Bridge data is widely used for determining histories of channel change (Piest, Elliott, and Spomer 1977; Kellerhals 1982; Simon and Rinaldi 2000; M. J. Daniels 2002). Although the magnitude of the uncertainties was unknown, it is realistic to assume that some variance in the incision measurements could be attributed to these uncertainties. Despite this, the data compiled represent the best historical record of stream incision on tributaries to the Nebraska reach of the Missouri River.

Rates of Channel Incision on the Missouri and Its Tributaries

Graf (1977) identified a rate law in which the response of a geomorphic system to an exogenous forcing factor will be delayed and then proceed at a rapid rate. Once initiated, response will decrease at an exponential rate until the system asymptotically approaches a new dynamic equilibrium. We adopt this model as a hypothesis with depth of channel incision as the response (dependent) variable utilizing this equation:

$$\ln Id_t = \ln Id_f - bt \quad (1)$$

where Id_t is depth of incision at time t, Id_f is final depth of incision, t is the number of years since incision was first initiated, and b is the rate constant estimated through regression.

To empirically estimate this model, we draw from two data sources: (1) Missouri River gage records at Yankton, Maskell, Sioux City, and Decatur; and (2) cross-sectional data from thirty-six sites along fifteen Missouri River tributaries (Rus, Dietsch, and Simon 2003). Most sites used included at least five thalweg streambed elevation measurements and some had up to fifty. Together these provide an empirical basis for assessing the rate of channel incision on the main stem Missouri River and its tributaries.

Spatial Patterns of Channel Incision

The depth of base-level lowering is a key independent variable explaining depth of incision (Pickup 1977; Schumm, Mosley, and Weaver 1987). This was quantified as either (1) the change in Missouri River stage at the watershed outlet (see Figure 7A) or (2) the change in bed elevation of a downstream channelized site. Base-level lowering identified using these two methods was not significantly different at 95 percent.

From the literature, other variables were identified that have been found to influence channel incision. These include distance upstream from location of base-level lowering (Brush and Wolman 1960; Simon 1992), basin area (M. J. Daniels 2002), extent of agricultural development upstream from the point of estimated incision (Piest, Elliott, and Spomer 1977), geologic considerations such as cohesiveness of bed and bank materials and presence of bedrock (Thorne 1999), and the presence of channelized reaches and grade control structures. Consistent with previous studies, explanatory variables selected for inclusion in this model were based on spatial representations of topography, climate, and land use as geographic information system (GIS) layers. The change in percentage of upstream area in agricultural production from 1950 to 2000 was derived from county-level historical data (Waisanen and Bliss 2002). Slope was derived from digital elevation models (DEMs). Using the D8 algorithm (O'Callaghan and Mark 1984), DEM data also were used to determine upstream drainage area.

To create a measure that captures the process of upstream propagation of incision, we developed a *flow-length ratio* that represents the proportion of the flow distance from the point of measured base-level lowering to the drainage divide along the flow line as determined from DEM data (Figure 9). The flow-length value is 1 at the point of base-level lowering and 0 along

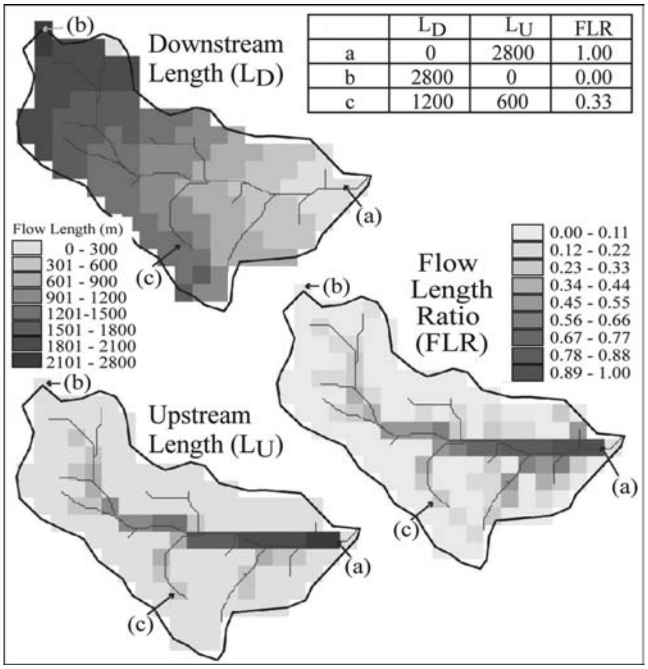

Figure 9. A ratio of upstream and downstream flow-length raster layers are combined using map algebra to form a flow-length ratio FLR = $L_U/(L_U + L_D)$, where L_U is the upstream flow length to the farthest divide and L_D is the flow length to the basin outlet (defined here as the point of base-level lowering). As shown in this hypothetical watershed, the resulting layer possesses values that range from 0 at the basin boundaries to 1 at the outlet, independent of basin size.

the entire watershed divide, with intermediate values along the channel network that can be determined using DEM data for any point on a stream. Flow-length ratio therefore represents relative hydrologic distance from the watershed boundary to the basin outlet. Raw flow-length ratios resulted in gaps at tributary junctions. To enforce accordant junction levels, we wrote an ArcView Avenue script that applies the flow-length ratio in an iterative manner by stream order. The Avenue script is available for download at http://www.augustana.edu/users/ggheine/incision_proj.htm. Mean and standard deviation values for all variables used in the analysis are shown in Table 1. Variables that were not normally distributed were transformed and found to be log-normal.

Ordinary least squares (OLS) multiple regression procedures were used using JMPIN statistical software (2000) to develop a model explaining streambed elevation change. Depth of incision was normally distributed with a mean of 127.4 cm (Figure 10). To isolate the effects of the flow-length ratio, sites upstream of known grade control structures and channelized reaches were omitted in the first model. Considering the

Table 1. Dependent and independent variables used in regression models predicting streambed elevation change

Variable	*M*	*SD*
Measured at point-specific locations		
Streambed elevation change (m)	–1.27	0.85
Base-level lowering (BLL) (m)	–2.32	1.22
Flow-length ratio (FLR)	0.61	0.24
BLL*FLR	–1.32	0.85
Contributing area (30 × 30 m cells)	203	388
Log contributing area ($base_{10}$)	1.91	0.58
Downstream length (m)	18,638	15,746
Log downstream length ($base_e$)	9.38	1.09
Upstream length (m)	27,145	29,113
Log upstream length ($base_e$)	9.88	0.77
Measured for tributary watershed		
Average slope (degrees)	3.33	0.78
Maximum slope (degrees)	23.0	9.22
Log maximum slope ($base_e$)	3.06	0.38
Measured for flow-accumulation area of cross-section sites		
Mean slope (degrees)	3.23	0.91
Mean change in SCS curve number	14.6	1.6
Upstream row crop (% of area)	56.1	18.4
Percentage change in agricultural land (1950–2000)	–5.95	3.26

Note: SCS = Soil Conservation Service.

small sample size in this analysis ($n = 47$), traditional split-sample validation was not possible. Instead, uncertainties for the equations were quantified by the average standard error of prediction (ASEP). This methodology has been widely used in similar studies carried out by the U.S. Geological Survey in flood-flow estimation at ungaged stream sites (e.g., Eash 2001). In addition to the uncertainty analysis, the four measurement sites within the Weeping Willow Creek drainage network were withheld from model calibration for the purpose of model validation. Validation was performed by comparing model predictions to measured values at the four sites using root mean square error.

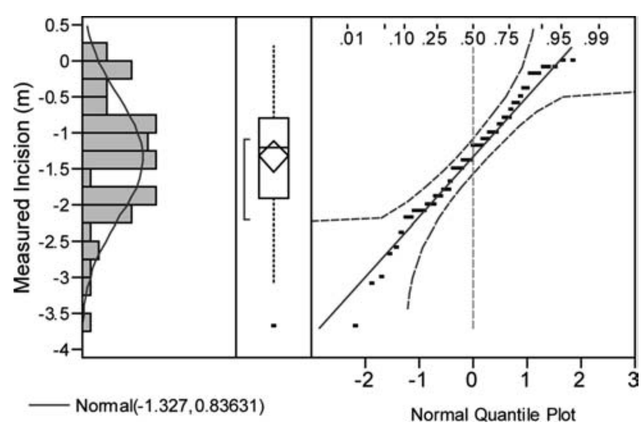

Figure 10. Normal distribution of measured streambed elevation change on sixty-three tributary streams.

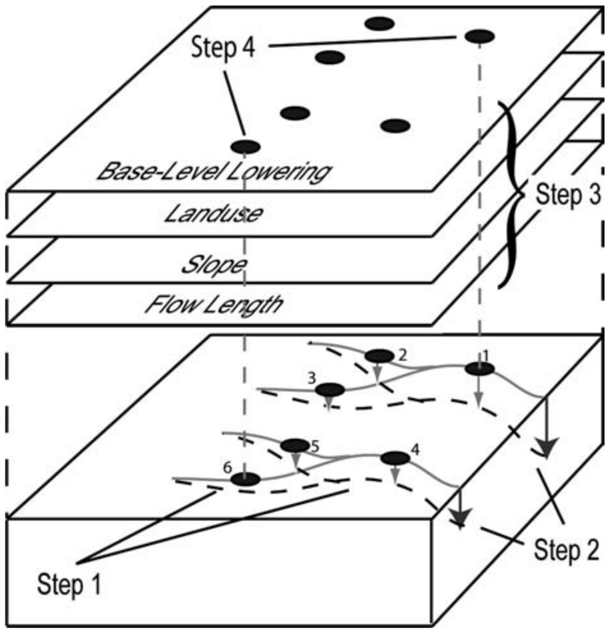

Figure 11. Steps used in the research design emphasizing spatial relationships in GIS data layers. Step 1: Stream-site GIS layer creation. Step 2: Locating points of base-level lowering. Step 3: Overlay analysis between stream sites and other x variables. Step 4: Regression model extrapolation to all other sites along stream reaches.

Map algebra was subsequently used to estimate incision associated with Missouri River degradation throughout tributary channel networks by (1) converting cross-section sites to a point file using GIS software (ArcMap 2004), (2) locating points of base-level lowering, and (3) creating GIS layers of potential explanatory variables (Figure 11). Significant explanatory variables were applied to calculate predicted depth of incision for all locations along the tributary drainage networks within the study area through map algebra (Figure 12). Analyzed tributary networks were based on the medium-scale National Hydrographic Dataset (NHD), but this revealed a well-known data quality issue common to these published channel networks: The NHD data (in which stream channels are based on the blue-line hydrography on the topographic maps) are found to be inconsistent between adjacent map sheets. Methods described in Heine, Lant, and Sengupta (2004) were used to create an improved representation of stream channels based on the average drainage area above the source of each blue line. Once the channel network was resolved, a spatial representation of point-specific estimates of tributary incision was completed

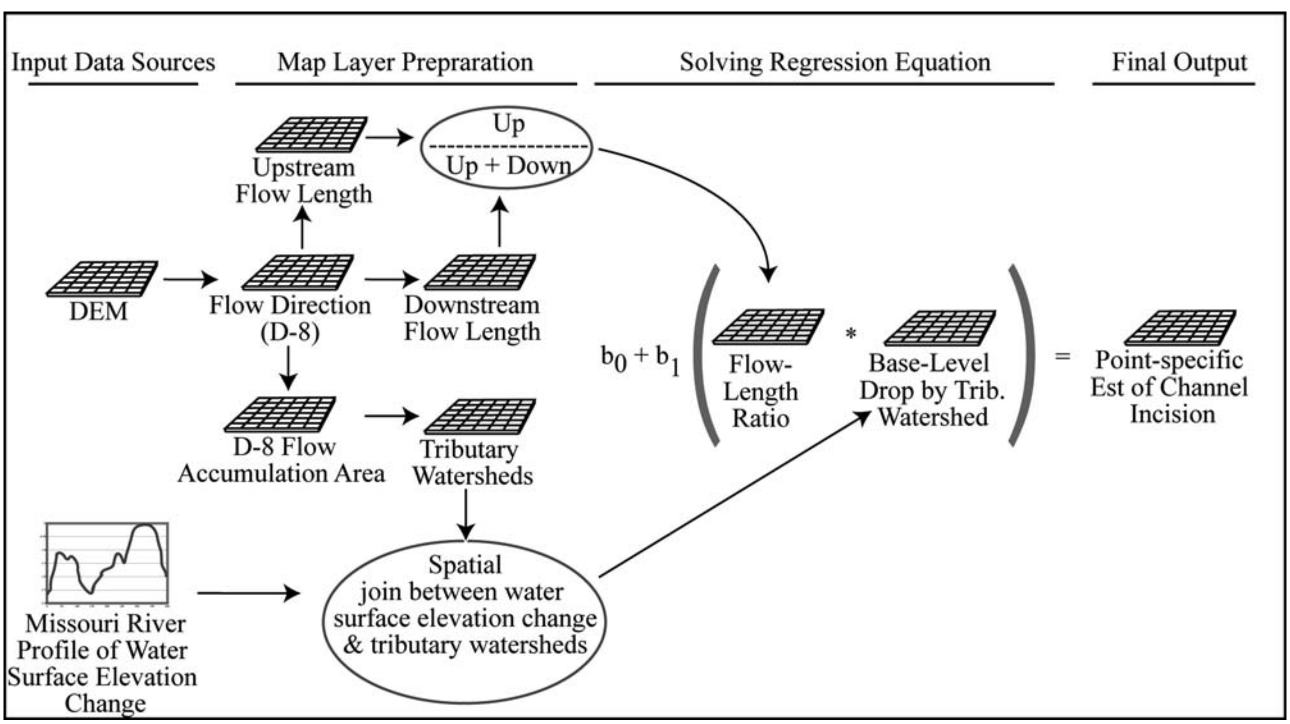

Figure 12. Simplified cartographic model showing data, GIS layers, and processing steps in creating the stream incision map from the product of base-level lowering and flow-length ratio. There were no other significant explanatory variables for depth of incision.

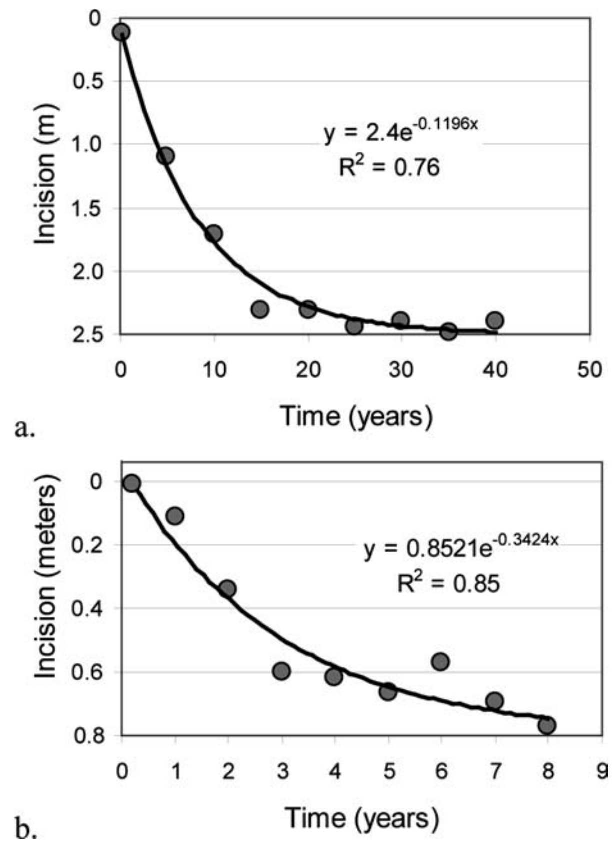

Figure 13. Results of log-linear regression of rate of incision over time for representative locations on (A) the Missouri River (Decatur) and (B) New York Creek tributary near Spiker, Nebraska (U.S. Geological Survey stream gage number 06608700).

by using the map algebra functionality in ArcGIS and extrapolating the statistical model to all streams in the study area with a raster cell spacing of thirty meters.

Sixteen sites were reintroduced in a second regression model to test the effects of grade control structures and channelization on stream channel incision. Model parameters were derived using the same methods as in the first spatial pattern regression model. Note that these variables could not be included in the map algebra extrapolation because the location of each channelized reach or grade control structure throughout the Nebraska–Iowa loess region would have to be known so that their upstream effects could be accounted for at each raster cell containing a stream. These data exist only for the gaging sites, not for each stream in the loess region.

Results

Temporal Patterns and Rates of Channel Incision

Following the closure of large reservoirs in 1954 and 1955, channel degradation on the Missouri River closely followed the rate law function described in Equation 1 (Figure 13A) with R^2 ranging from 0.82 to 0.91 at the four sites studied (Table 2). Half of total degradation takes place in about five years starting in 1955 at Yankton and in 1960 or 1965 at downstream locations. Approximating Graf's (1977) concept of relaxation time, 95 percent of incision (4.32 half-lives) took place in eighteen to twenty-five years and 99 percent (6.65 half-lives) took place in twenty-eight to thirty-nine years. On tributaries, most results also confirm the Graf (1977) rate law model (Figure 13B), with twenty-six of thirty-six sites achieving an R^2 of 0.8 or greater. Half-lives vary from 2.0 to 9.0, years with corresponding relaxation times ranging from eight to thirty-nine years for 95 percent of total incision or thirteen to sixty years to achieve 99 percent of total incision (Table 2). Simon and Rinaldi also found very strong confirmation of Graf's model on the West Tarkio Creek on the Iowa–Missouri border within the loess region, with R^2 ranging from 0.96 to 0.98. Their study, however, shows a somewhat longer eighty-year period of adjustment with half-lives of ten to twenty years.

Spatial Patterns of Channel Incision

Considering first the regression model using only the forty-seven cross sections on reaches lacking channelization and grade controls, the correlation matrix shows that depth of incision is positively correlated with flow-length ratio ($r = 0.34$), and with downstream base-level lowering ($r = 0.61$), and highly positively correlated with the product of these two variables ($r = 0.86$; Table 3). Depth of incision is not significantly correlated (0.05) with other watershed parameters such as slope, land use, or land use change. Several independent variables are intercorrelated at a 0.01 level of significance where variables are used in both linear and log forms (e.g., mean basin slope), where they are components of an interaction term or ratio (e.g., base-level lowering and BLL*FLR, flow-length ratio, and downstream length), or where they have a strong hydrologic association (e.g., log contributing area with log upstream length and log max basin slope). In addition, highly significant positive correlations occur among mean change in Soil Conservation Service (SCS) curve number, percentage of upstream area in row crops, and log max basin slope, variables that reflect the vulnerability of lands in the watershed to sheet and rill erosion.

For model calibration, we used forward, backward, and combined stepwise methods to identify combinations of significant explanatory variables. We included only explanatory variables that were statistically

Table 2. Regression results based on application of rate law Equation 1 from Graf (1977) for the Missouri River and tributaries

Site no.	Site name	Total incision (m)	No. of cross sections (n)	Rate coefficient (b)	R^2	Half-life (years)	Years for 95% of total incision	Years for 99% of total incision
	Missouri River							
1	Yankton	2.7	10	0.163	0.82	4.3	18.6	28.6
2	Maskell	1.3	8	0.177	0.91	4.2	18.1	28.0
3	Sioux City	2.2	9	0.152	0.85	5.3	22.9	35.2
4	Decatur	2.4	9	0.120	0.76	5.8	25.1	38.6
	Tributaries							
7	New York Cr.	0.9	49	0.342	0.85	2.0	8.6	13.3
10	Kezan Cr.	0.3	4	0.295	0.99	2.3	9.9	15.3
27	N. Nemaha R.	1.3	8	0.260	0.82	2.7	11.7	18.0
26	Yankee Cr.	2.5	4	0.244	0.94	2.8	12.1	18.6
9	N. Big Blue	0.9	6	0.224	0.99	3.1	13.4	20.6
36	Lit. Nemaha	2.0	6	0.207	0.68	3.4	14.7	22.6
8	Lit. Papillion Cr.	2.2	5	0.207	0.99	3.4	14.7	22.6
41	W. Papillion Cr.	5.3	8	0.202	0.80	3.4	14.7	22.6
32	Spring Cr.	1.4	5	0.194	0.98	3.6	15.6	23.9
30	Muddy Cr.	6.6	5	0.188	0.85	3.7	16.0	24.6
14	Coon Cr.	1.7	5	0.182	0.50	3.8	16.4	25.3
21	S. Omaha Cr.	2.3	42	0.182	0.96	3.8	16.4	25.3
23	Rock Cr.	1.9	6	0.176	0.85	3.9	16.8	25.9
20	Lit. Papillion Cr.	0.6	31	0.172	0.90	4.0	17.3	26.6
25	S. Fk Lit. Nemaha R.	0.6	22	0.170	0.81	4.1	17.7	27.3
11	N. Fk Lit. Nemaha R.	0.9	5	0.170	0.99	4.1	17.7	27.3
38	Weeping Water Cr.	1.1	48	0.161	0.68	4.3	18.6	28.6
16	Rock Cr.	0.4	4	0.156	0.93	4.5	19.4	29.9
37	Weeping Water Cr.	1.0	49	0.150	0.99	4.6	19.9	30.6
15	Muddy Cr.	5.3	5	0.139	0.82	5.0	21.6	33.3
24	Mid. Br Big Nemaha R.	1.5	5	0.129	0.69	5.4	23.3	35.9
22	N. Fk Big Nemaha R.	1.5	7	0.129	0.69	5.4	23.3	35.9
39	Wahoo Cr.	0.6	30	0.128	0.56	5.4	23.3	35.9
17	Olive Br.	0.6	10	0.128	0.95	5.4	23.3	35.9
6	Lit. Nemaha R.	0.9	6	0.124	0.94	5.6	24.2	37.2
13	Lit. Salt Cr.	2.3	18	0.113	0.81	6.1	26.4	40.6
19	Elkhorn R.	1.2	48	0.113	0.81	6.2	26.8	41.2
12	Salt Cr.	0.7	21	0.109	0.89	6.4	27.6	42.6
29	Sand Cr.	1.8	6	0.105	0.62	6.6	28.5	43.9
35	Oak Cr.	3.4	8	0.104	0.76	6.7	28.9	44.6
33	Yankee Cr.	2.6	8	0.100	0.81	6.9	29.8	45.9
31	Wolf Cr.	3.0	80	0.099	0.91	7.0	30.2	46.6
34	S. Fk Lit. Nemaha R.	5.4	6	0.091	0.83	7.7	33.3	51.2
28	Elk Cr.	3.7	8	0.088	0.72	7.9	34.1	52.5
18	Rock Cr.	2.2	6	0.084	0.78	8.2	35.4	54.5
40	Maple Cr.	2.5	31	0.077	0.96	9.0	38.9	59.9

Note: Sites are ordered from shortest to longest half-life. Relaxation times are shown for 95 percent and 99 percent of total incision. Site numbers are shown in Figure 8B.

significant at the 95 percent confidence level and that (1) maximize the adjusted R^2 and (2) minimize the Mallows Cp statistic (Mallows 1973) designed to achieve a compromise between the number of included variables and explained variance in the model. Each of the variable selection procedures provided the same result: a one-variable model in which the interaction term of base-level lowering times flow-length ratio (BLL*FLR) is the only significant variable. The model is highly significant and achieves an R^2 value of 0.73 (Figure 14). The residuals of the calibrated regression are normally distributed and homoscedastic. Given that the intercept is small and negative, and an intercept of 0 makes sense theoretically (incision should be zero at the drainage

Table 3. Correlation matrix for dependent and independent variables used in the analysis

Variable	1) Measured incision	2) BLL*FLR	3) Flow-length ratio (FLR)	4) Base-level lowering (BLL)	5) Log (contributing area)	6) Downstream length	7) Log (upstream length)	8) Mean basin slope	9) Log (max basin slope)	10) Mean upstream slope	11) Mean change in SCS curve no.	12) % of upstream area in row crops	13) % change in row crops 1950–2000
1) Measured incision		0.000	0.278	0.000	0.158	0.208	0.196	0.071	0.172	0.797	0.326	0.384	0.480
2) BLL*FLR	0.86		0.006	0.000	0.139	0.053	0.167	0.067	0.145	0.937	0.439	0.365	0.385
3) Flow-length ratio (FLR)	0.34	–0.41		0.051	0.004	0.000	0.000	0.150	0.095	0.367	0.228	0.566	0.767
4) Base-level lowering (BLL)	0.61	0.69	0.30		0.795	0.023	0.578	0.007	0.018	0.458	0.850	0.275	0.387
5) Log (contributing area)	0.22	–0.23	0.43	0.04		0.713	0.000	0.096	0.000	0.161	0.000	0.000	0.037
6) Downstream length	0.20	0.30	–0.79	–0.35	0.06		0.970	0.935	0.332	0.868	0.285	0.044	0.363
7) Log (upstream length)	0.20	–0.21	0.52	0.09	0.97	–0.01		0.097	0.000	0.299	0.000	0.000	0.032
8) Mean basin slope	0.28	0.28	0.22	0.40	0.26	–0.01	0.26		0.000	0.000	0.025	0.005	0.002
9) Log (max basin slope)	0.21	0.23	0.26	0.36	0.60	0.15	0.63	0.73		0.009	0.000	0.000	0.000
10) Mean upstream slope	0.04	0.01	0.14	0.12	0.22	–0.03	0.16	0.71	0.39		0.407	0.472	0.117
11) Mean change in SCS curve no.	0.15	–0.12	0.19	–0.03	0.62	0.17	0.58	0.34	0.55	0.13		0.000	0.156
12) % of upstream area in row crops	0.14	0.14	0.09	0.17	0.63	0.31	0.61	0.42	0.67	0.11	0.56		0.021
13) % change in row crops 1950–2000	0.11	0.11	0.05	0.14	0.32	0.14	0.33	0.47	0.54	0.24	0.22	0.35	

Note: Pearson's r correlations in lower left; corresponding significance level in upper right. SCS = Soil Conservation Service.

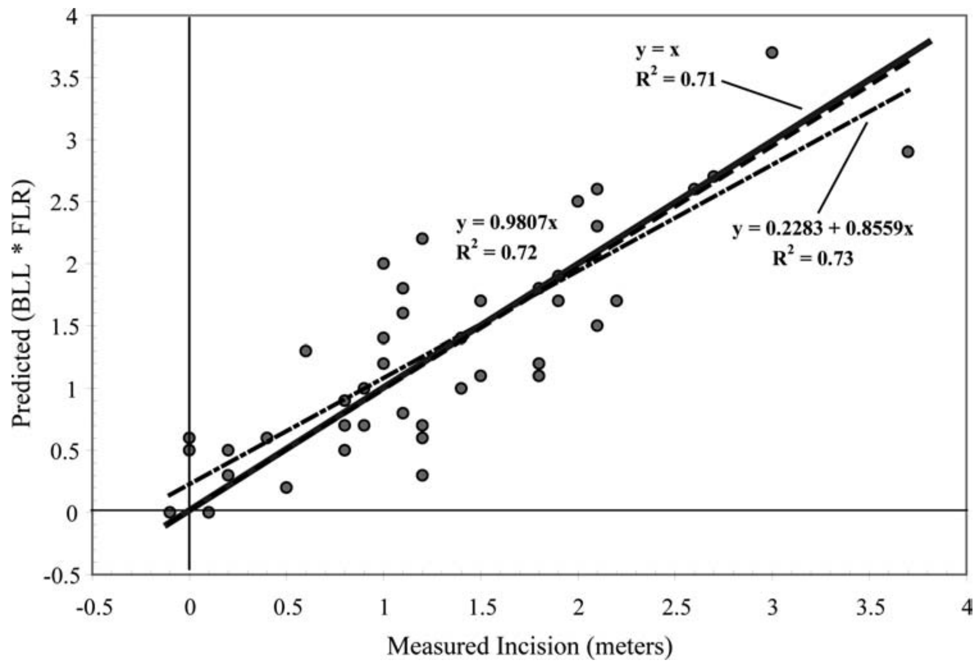

Figure 14. Regression lines fitted between measured channel incision and Base-Level Lowering * Flow-Length Ratio for the forty-seven sites using the calibrated model ($R^2 = 0.73$), the model with an intercept of zero ($R^2 = 0.72$), and a model with an intercept of zero and a coefficient of 1 ($y = x$) ($R^2 = 0.71$).

divide or with no base-level lowering), we also developed a model forcing the intercept to zero. This model performed nearly as well ($R^2 = 0.72$) and resulted in a regression coefficient on BLL*FLR of 0.98, very close to 1 (Figure 14). Thus, the simple equation:

$$I_d = \text{BLL}^* \text{ FLR} \quad (2)$$

where I_d is depth of incision, provides a very close approximation to the empirically derived model using the forty-seven cross sections. In the next section, we discuss the theoretical implications of Equation 2.

As an additional form of validation, one tributary watershed (Weeping Willow; see Figure 8) was withheld from the model and the calibrated model was used to estimate depth of incision as a comparison to measured depth. The results show a root mean square error of 0.395, less than the ASEP of 0.45 m, suggesting an accurate assessment of error (Table 4).

Spatial Extrapolation

The calibrated regression model shown in Figure 14 was applied to all tributary drainage networks in the study area using map algebra by creating a GIS raster layer for base-level lowering and flow-length ratio and then calculating the calibrated regression equation at each 30 m raster cell along the length of all tributary drainage networks. At stream junctions, the estimated incision of the truck stream was used as the base-level lowering for the tributary stream, and flow-length ratio was recalculated for the tributary watershed. The incision map thus takes the form of a spatial data layer of point-specific streambed elevation change at every 30 m cell location along the length of all tributary drainage networks of the middle Missouri River (Figure 15). The complete results are contained in an Atlas of Incision available at http://www.augustana.edu/users/ggheine/incision_proj.htm. Using the resulting information, we find that 4,100 km of stream channels are predicted to have incised by

Table 4. Analysis of errors at four streambed elevation sites (SBE = 0.897(BLL*FLR) – 0.150)

Site ID	Measured streambed elevation change (m)	Modeled streambed elevation change (m)	Square errors (m)
MRT-13	–0.8	–0.50	0.106
MRT-14	–0.6	–1.20	0.403
MRT-15	–1.0	–1.30	0.109
MRT-16	–2.1	–2.20	0.007
		SSE	0.625
		RMSE	0.395

Note: Note that results are slightly different than in Figure 14 because four stations are withheld for model validation. SSE = sum square errors; RMSE = root mean square error.

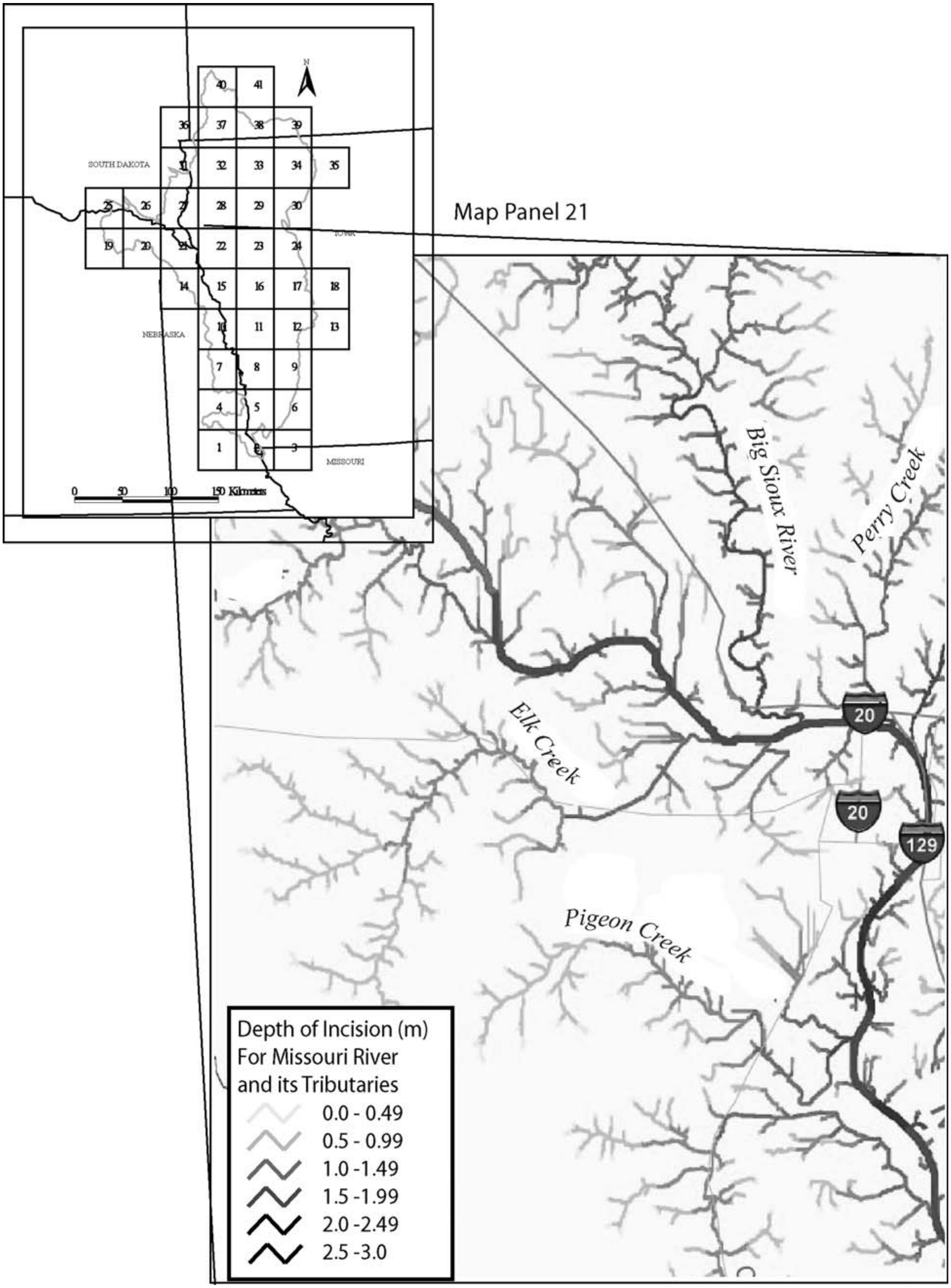

Figure 15. Spatial patterns of stream incision on tributaries of the Nebraska reach of the Missouri River caused by lowering of base level at the Missouri River confluence. Panel 21 of the Atlas of Incision developed using map algebra is shown. The complete map is available at http://www.augustana.edu/users/ggheine/incision_proj.htm.

Table 5. Results of regression analysis on depth of incision using sixty-three sites and including channelization and grade control structures as dummy variables

Term	Estimate	*SE*	*t* ratio	Prob > |*t*|
Intercept	–0.051	0.125	–0.41	0.686
BLL*FLR	0.805	0.066	12.17	< .0001
Grade control structure (0/1)	–0.492	0.085	–5.77	< .0001
Channelization (0/1)	0.331	0.074	4.45	< .0001

Note: $N = 63$, $R^2 = 0.76$, adjusted $R^2 = 0.74$; root mean square error = 0.42 m. BLL = base-level lowering; FLR = flow-length ratio.

one meter or more due to Missouri River degradation, whereas 16,600 km are predicted to have incised by at least the standard error of prediction value of 0.45 m.

When sixteen sites upstream of grade control structures or channelized reaches are reintroduced to total sixty-three sites, the regression model achieves a slightly higher R^2 of 0.76, with BLL*FLR as the most significant explanatory variable. In this model, channel incision is 0.49 m less when there are downstream grade control structures and 0.33 m greater when there is downstream channelization (Table 5).

Discussion

In this study, the rate law proposed by Graf (1977) effectively captures the temporal dynamics of stream channel incision in the loess-dominated region of the Missouri River and its tributaries. Incision was induced on the Missouri River downstream of reservoirs and by wing dams and meander cutoffs. Knickpoints have proceeded up tributaries with the total magnitude of down cutting at a given point predominantly controlled by the lowering of base level at the Missouri confluence times the flow-length ratio (the proportion of flow distance from the basin boundary to the outlet). Channels have responded to base-level lowering due to channelization of a downstream reach by incising in the same manner. A model using the single interaction term (BLL*FLR) and no coefficients captures 71 percent of the variance in stream incision. We found no evidence of a complex response; there were no periods of aggradation downstream of areas of active incision and knickpoint migration.

These results reflect geomorphic dynamics captured by the flume experiments described in Schumm, Harvey, and Weaver (1987). Like a flume, the study area contains relatively simple conditions, including a geologically uniform erodible loess substrate in which channel readjustment to base-level lowering is nearly completed in just one to three decades. These results are also consistent with the work of other fluvial geomorphologists such as Galay (1983), Germanoski and Ritter (1988), and Simon and Rinaldi (2006). This suggests that, in the absence of complex geology and when the process of stream channel adjustment to base-level lowering approaches completion, the spatial and temporal complexities involved in the process of incision and knickpoint propagation can be largely encapsulated in the simple equation I_d = BLL*FLR.

Conceptual Model of Stream Channel Incision

These results can be captured in a conceptual model of stream incision as illustrated in Figure 16. Following sediment capture, incision proceeds rapidly down the trunk river (the Missouri in this study) and proceeds with a half-life of about five years. This process establishes a lower base level for tributary streams. Following base-level lowering, knickpoints travel upstream, advancing up tributaries following Playfair's Rule, which calls for tributaries to join their master streams at accordant elevations (Figure 16A). The overall rate of incision decreases exponentially over time, asymptotically approaching a new dynamic equilibrium. Time required for knickpoint migration (Figure 16B) is a function of the erodability of geologic substrates and can vary by orders of magnitude in different environments ranging from loess to granite. Once this new equilibrium is established, incision depths follow the simple equation of I_d = BLL*FLR. From a theoretical perspective, use of the flow-length ratio suggests that the incision of a drainage network is scale-independent; a point 50 percent of the distance up an affected drainage basin would be expected to exhibit 50 percent of the magnitude of the base-level lowering at its outlet.

Where it is not uniform, however, geology plays a critical role in making the spatial pattern of incision more complex. The occurrence of less erodable substrates, or their deliberate introduction through such means as grade control structures, has the effect of greatly slowing upstream propagation of incision knickpoints (Figure 16C). Depth of incision upstream of such a barrier equals BLL*FLR with a smaller base-level lowering determined at the less erosive structure. Channelization or meander cutoffs have the reverse effect, increasing base-level lowering and propagating an incision wave upstream from that point as determined by the flow-length ratio calculated from the upstream end of the affected reach (Figure 16D). Rus, Dietsch,

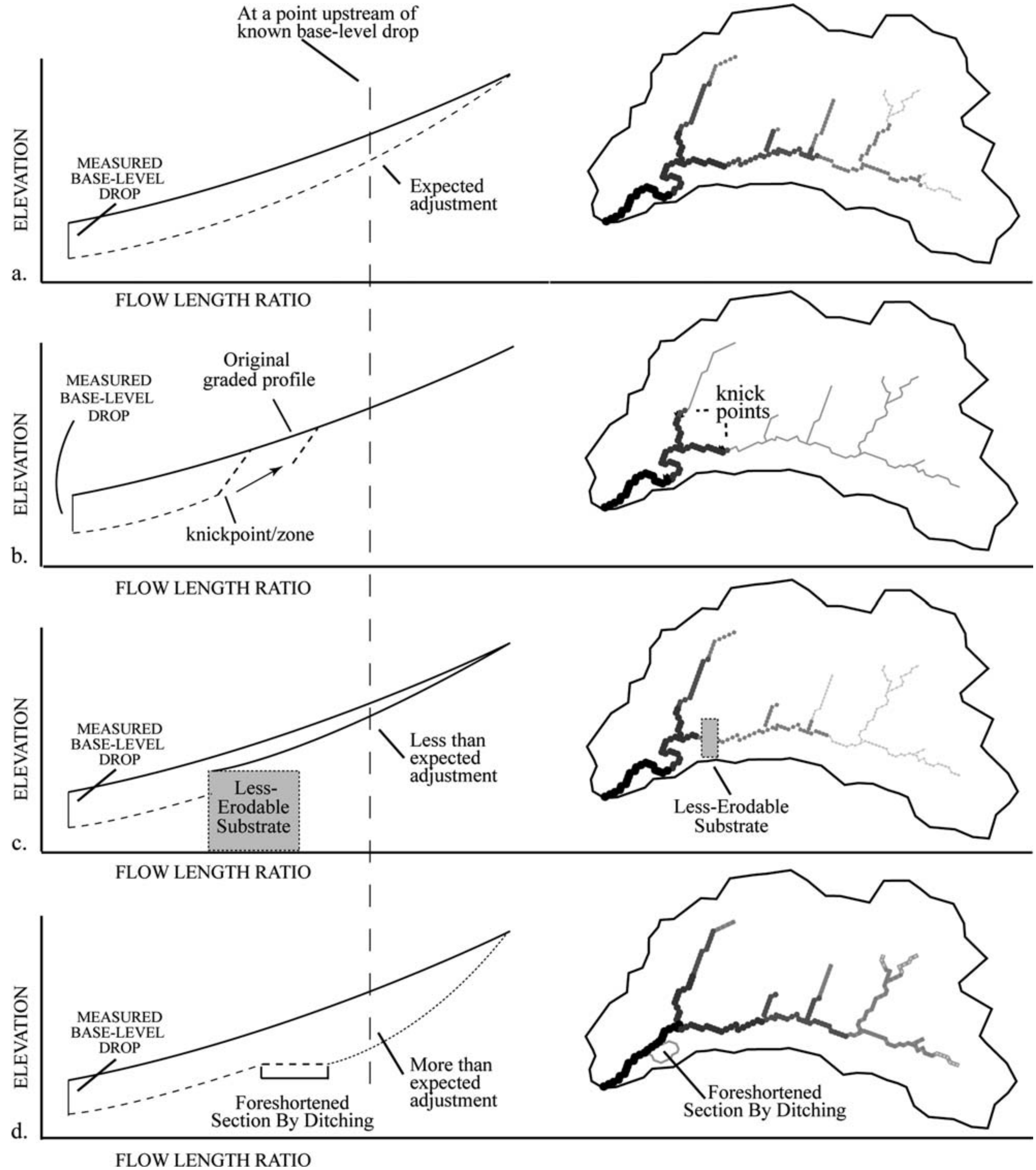

Figure 16. (A) The watershed-scale spatial pattern of incision based on $I_d = \text{BLL*FLR}$. Expected longitudinal pattern is shown on the left and corresponding spatial manifestations of stream incision are shown on the right with relative depths of incision indicated by grayscale. Variations to the pattern of longitudinal adjustment to a base-level lowering in response to (B) time, with incision at any one point following the rate law, (C) geological variability, and (D) channelization.

and Simon (2003) documented eight meters of incision on the heavily channelized upper Nemaha, five meters on the Little Nemaha (see Figure 2), and five meters on the Papillion Creek; and Piest, Elliott, and Spomer (1977) found six meters of degradation on the Tarkio Drainage System, all upstream of channelized reaches in western Iowa. Each of these depths of incision exceeds twentieth-century Missouri River degradation and

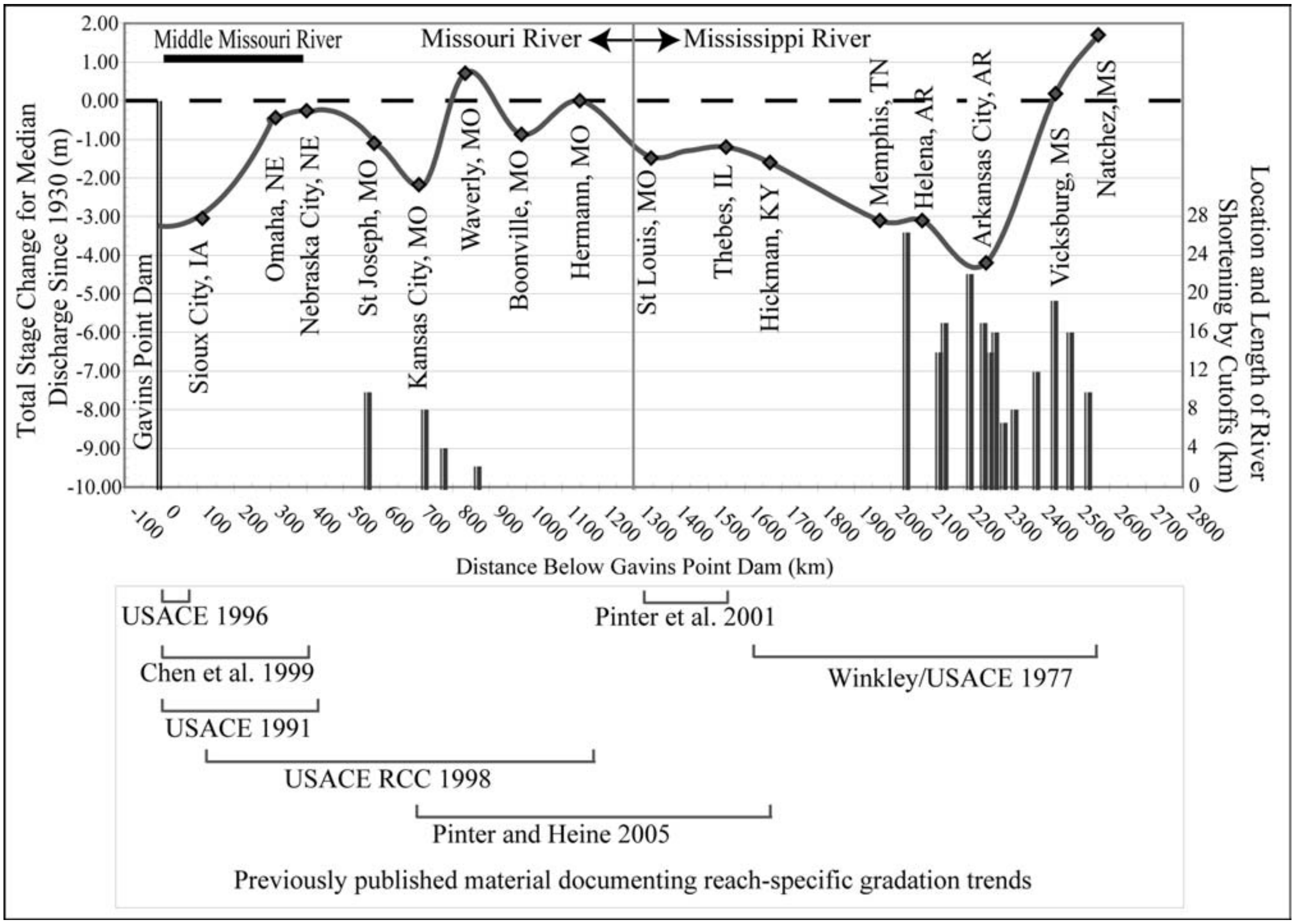

Figure 17. Published trends in water-surface elevation from the Gavins Point Dam to the Gulf of Mexico using specific gage results from preexisting studies. Black dots are locations of gages; the gray line is an artistic spline merely connecting the gages along the profile. The bars at bottom are the location and magnitude of human-caused meander cutoffs. Sources are shown with respect to river reach studied.

suggests additional causes of channel incision in the region, such as local channelization.

Most watersheds affected by stream incision have a combination of these factors at work, and other streams may exhibit additional complexities and feedbacks that were absent from our study area. Nevertheless, we propose that this model captures the primary factors affecting the watershed-scale pattern of stream channel incision.

Further Research

Given that stream channel incision is a widespread and damaging phenomenon, there is a need for studies in regions that lack the flume-like simplicity of the Missouri River loess region. Other reaches of the Missouri–Mississippi River system also exhibit severe stream channel incision (Figure 17). For example, on the White River, which enters the Mississippi from the west near Arkansas City, severe stream channel incision has recently resulted in the need for a $262 million lock and dam (U.S. Army Corps of Engineers 1993) and replacement of damaged bridges. Changes in streambed elevation since 1930 from Gavins Point Dam 2,800 km downstream to Natchez, Mississippi (Figure 17), show that Mississippi River channel degradation along the Arkansas border (below Memphis, Tennessee, to above Vicksburg, Mississippi) exceeds that of the Nebraska reach of the Missouri River. Channel degradation on the lower Mississsippi River and on the Missouri River near Kansas City, Missouri, are associated with twentieth-century meander cutoffs, but these relationships and other possible contributing mechanisms such as wing dams (dikes) and levees have not been fully explored. Moreover, there is widespread evidence of tributary incision in Arkansas and Mississippi, such as on the White and Homochitto Rivers. The spatial association between tributary incision and

Mississippi degradation, taking into account time and the more complex geology of the region, has also not been well established.

Conclusions

Understanding the geomorphic processes, cause-and-effect linkages, and spatial patterns of channel incision has significant implications for aquatic and riparian ecology, river engineering and management, and effective stream restoration. Focusing on the incised tributaries of the Missouri River from Gavins Point Dam to the Nebraska–Kansas state line, it was found that the Missouri River, following a rate law function with a half-life of only about five years, has degraded its bed by as much as four meters due to reservoir sedimentation. Incision of tributary channels is strongly associated with the lowering in elevation of the mainstem Missouri and proceeds at rates with half-lives ranging from two to nine years. The flow-length ratio estimates the proportion of this base-level lowering that propagates to any point upstream, supporting the findings of previous flume studies at this larger scale. When sixteen sites with downstream grade control structures and channelized reaches are excluded, the product of base-level lowering and flow-length ratio captures 71 percent of the variance in depth of incision with a root mean square error of 0.42 m. This result suggests that Missouri River degradation is the dominant cause of tributary stream incision in the eastern Nebraska and western Iowa region. A map algebra technique was developed to extrapolate the regression-based estimates to each thirty-meter raster cell along all tributary streams of the Missouri River, producing a map of estimated stream incision due to Missouri River degradation. Regression analysis also confirms that grade control structures reduce upstream migration of incision, and channelization produces local incision following the same base-level lowering times flow-length ratio model. Therefore, in variable geologic settings, or where adjustment to base-level lowering is incomplete, spatial patterns of observed incision will be more complex, reflecting the influences of channelization, the erodability of geologic materials, and time.

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