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DOWNSTREAM EFFECTS OF DAMS ON CHANNEL GEOMETRY AND BOTTOMLAND VEGETATION: REGIONAL PATTERNS IN THE GREAT PLAINS

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Abstract: The response of rivers and riparian forests to upstream dams shows a regional pattern related to physiographic and climatic factors that influence channel geometry. We carried out a spatial analysis of the response of channel geometry to 35 dams in the Great Plains and Central Lowlands, USA. The principal response of a braided channel to an upstream dam is channel-narrowing, and the principal response of a meandering channel is a reduction in channel migration rate. Prior to water management, braided channels were most common in the southwestern Plains where sand is abundant, whereas meandering channels were most common in the northern and eastern Plains. The dominant response to upstream dams has been channel-narrowing in the southwestern Plains (e.g., six of nine cases in the High Plains) and reduction in migration rate in the north and east (e.g., all of twelve cases in the Missouri Plateau aud Western Lake Regions). Channel-narrowing is associated with a burst of establishment of native and exotic woody riparian pioneer species on the former channel bed. In contrast, reduction in channel migration rate is associated with a decrease in reproduction of woody riparian pioneers. Thus, riparian pioneer forests along large rivers in the southwestern Plaius have temporarily increased following dam construction while such forests in the north and east have decreased. These patterns explain apparent contradictions in conclusions of studies that focused on single rivers or small regions and provide a framework for predicting effects of dams on large rivers in the Great Plains and elsewhere. These conclusions are valid only for large rivers. A spatial analysis of channel width along 286 streams ranging in mean annual discharge from 0.004 to 1370 cubic meters per second did not produce the same clear regional pattern, in part because the channel geometries of small and large streams are affected differently by a sandy watershed.

Key Words: channel geometry, cottonwood, dam, forest, Great Plains, riparian, sediment

INTRODUCTION

Most large rivers in the Northern Hemisphere have been dammed (Dynesius and Nilsson 1994), and downstream lotic and riparian ecosystems have been greatly altered (Brinson et al. 1981, Stanford et al. 1996). Prediction of the downstream changes in channel geometry and biotic community composition is complicated by the diversity of possible responses. Following dam construction, rivers may become wider, narrower, shallower, or deeper; time necessary for the response ranges from months to millennia, and the direction of the response may change over time (Petts 1979, Williams and Wolman 1984). Response of the riparian ecosystem is equally complex, even within the Great Plains (Friedman et al. 1997). For example, downstream cottonwood forests have typically decreased in Alberta (Rood and Mahoney 1990) but increased in Nebraska and Colorado (Johnson 1994). The diversity of dam effects occurs because channel response is mediated by fluvial processes that vary in relative importance from site to site. Where the dominant fluvial processes are known, methods for predicting the amount and timing of downstream channel response can be developed (Osterkamp and Hedman 1981, Church 1995), and the response of the riparian vegetation can be predicted (Scott et al. 1996, Johnson 1998). In this paper, we explore regional variation in the response of channel geometry to upstream dams in the Great Plains and part of the Central Lowlands in the United States. We relate this variation to the geologic and climatic factors that control local fluvial processes and discuss the consequences for riparian forests.

Ecological Characteristics of Riparian Pioneer Species

In Great-Plains riparian ecosystems, the narrow zone moist enough to support woody plants is also subject to frequent riverine disturbance. As a result, Plains riparian forests are often dominated by pioneer species, especially plains cottonwood (*P. deltoides* Marshall subsp. *monilifera* (Aiton) Eckenwalder), peachleaf willow (*Salix amygdaloides* Anderss.), and sandbar willow (*Salix exigua* Nutt.). In addition, the exotic shrub saltcedar (*Tamarix ramosissima* Ledebour) has become a dominant pioneer in the southern Great Plains and is naturalized as for north as southern Canada (Great Plains Flora Association 1986, Brock 1994). These pioneers have similar seedling-establishment requirements (White 1979). Freshly deposited alluvium typically provides ideal substrate for germination and establishment of abundant wind- and water-dispersed seeds, which are released beginning late each spring in association with peak river flows (Horton et al. 1960, Scott et al. 1993, Johnson 1994). The seeds lose germinability within a few weeks (Moss 1938, Ware and Penfound 1949, Horton et al. 1960). Riparian pioneers are intolerant of shade and rarely become established from seed under trees or herbs (Johnson et al. 1976, Friedman et al. 1995). Seedlings require a continuously moist surface during the first week or more of growth (Moss 1938), but adults typically avoid surface drought by extending roots down to the water table (Segelquist et al. 1993).

Riparian sites bare and moist enough for seedling establishment of riparian pioneers are usually close to the channel and subject to disturbance by the stream. Although pioneers are tolerant of burial and able to sprout from stems or roots, floods and ice scour typically cause high mortality of seedlings and saplings (Johnson 1994, Scott et al. 1996, Auble and Scott 1998). Therefore, establishment from seed occurs only in locations that are moist, bare, and protected from future intense disturbance (Everitt 1968, Bradley and Smith 1986, Johnson 1994).

Reproduction via sprouts from roots or stems may prolong occupation of a site (Rood et al. 1994). However, in the absence of physical disturbances such as floods, cottonwood and willow tend to be replaced by more shade-tolerant plants. In the eastern Plains, pioneer cottonwood and willow are replaced by a diverse bottomland hardwood forest (Bruner 1931, Weaver 1960, Johnson et al. 1976, Currier 1982). For example, in central Kansas, bottomland dominants include green ash (*Fraxinus pennsylvanica* Marsh.), bur oak (*Quercus macrocarpa* Michx.), American elm (*Ulmus americana* L.), box elder (*Acer negundo* L.), and hackberry (*Celtis occidentalis* L.; Weaver 1960). Compared to cottonwood and willow, these species are typically slower to disperse to new sites and are less tolerant of inundation, burial, physical damage, or soils low in organic matter (Johnson et al. 1976, Teskey and Hinckley 1978). Forest diversity decreases westward until only pioneer species remain. Thus, in much of the western Great Plains, the climax native bottomland community is not forest but shrubland or grassland (Hefley 1937, Lindauer 1983), and maintenance of forest is dependent upon physical disturbance, especially floods (Friedman et al. 1997, Auble and Scott 1998, Rood et al. 1998).

Downstream Effects of Dams on Channel Geometry and Forest Establishment

Dams typically decrease downstream peak flow and sediment load. Many different changes in channel geometry can result. For the purposes of this regional analysis, we only consider changes in planform (the two-dimensions of the ground surface as viewed from above). Vertical changes, especially channel-downcutting, are discussed by Petts (1979) and Williams and Wolman (1984), and their effects on riparian vegetation have been documented by Snyder and Miller (1991) and Rood et al. (1995). In the Great Plains, the two most common planform changes downstream from a dam are channel-narrowing and reduction in channel migration rate (Osterkamp and Hedman 1981). These two processes can have different effects on riparian pioneer forests.

If a dam reduces peak flows below that necessary to rework the entire channel bed, then vegetation may become established on the bed. The newly established vegetation promotes deposition of cohesive fine sediment and increases resistance to erosion (Smith 1976), thus stabilizing the channel at a narrower width. Furthermore, because sand and gravel are transported along the bed, a dam-related decrease in the load of such sediment decreases the equilibrium channel width necessary to transport the bedload. Because portions of former channel bed are bare, moist, and relatively safe from disturbance, they are ideal establishment sites for pioneer riparian vegetation. Therefore, post-dam channel-narrowing is typically associated with a pulse of woody pioneer establishment. This pulse ends when a new equilibrium width is attained. Further pioneer establishment occurs only to the extent that the channel is able to migrate.

Channel migration typically promotes establishment of riparian pioneers by providing new bare, moist surfaces such as point bars suitable for seedling establishment. If a dam reduces peak flow and sediment load, the rates of bank erosion and bar deposition are typically reduced. This effect may be exacerbated by

efforts to stabilize the channel banks or by channel incision resulting from sediment starvation. As channel migration rate decreases, there is a concomitant decrease in the frequency with which new sites suitable for establishment are created, which ultimately slows regeneration of pioneer species (Johnson et al. 1976, Bradley and Smith 1986, Rood and Mahoney 1990, Friedman et al. 1997). After many decades, riparian pioneers are replaced by more shade-tolerant species.

Interaction Between Channel Morphology and Dam Effect

Channel pattern strongly influences the relative importance of channel-narrowing and reduction in channel migration downstream from dams. Most Great Plains channels can be characterized as braided or meandering. Braided streams have steep gradient, high flow variability, and large sediment load dominated by coarse silt and sand (Osterkamp 1978). Braided channels are relatively wide and shallow because coarse sediment must be carried along the bed and forms banks that are easily eroded. For most of the year, most of the channel bed is not covered by water, and flow is contained in two to several stream branches that shift rapidly across the bed. In contrast, meandering streams are characterized by shallow gradient, low flow variability, and sediment load dominated by silt and finer particles (Leopold and Wolman 1957, Schumm 1960). Meandering channels are relatively narrow and deep because fine sediment can be carried throughout the water column and forms cohesive banks resistant to erosion. Most of the channel bed is under water year round.

Channel-narrowing downstream from dams is most extensive along braided channels because their wide, aerially exposed bed provides a large area suitable for vegetation establishment and because the large bed-sediment load necessary for braiding is usually removed by the dam. Furthermore, because large floods typically destroy the non-cohesive banks of braided channels, they often have a poorly developed floodplain prior to dam construction. Therefore, forest established along a braided channel during post-dam narrowing is often more extensive than the pre-existing forest (Stinnett et al. 1988, Johnson 1994, Miller et al. 1995).

Channel-narrowing is least likely to be important along meandering channels for two reasons. First, because the width-depth ratio is small, the area made available for vegetation establishment during channel-narrowing is relatively small. In fact, decreases in sediment load downstream from dams often cause erosion and non-equilibrium channel-widening in meandering channels (Williams and Wolman 1984). Second, because the area occupied by the channel is typically small compared to that occupied by the floodplain, forest established during channel-narrowing is typically much smaller than the area of pre-existing forest established gradually as a result of channel migration in the decades prior to flow regulation (Johnson et al. 1976). Therefore, along a meandering channel, the principal effect of reductions in peak flow is not channel-narrowing but reduced rate of channel migration (Friedman et al. 1997, Johnson 1998).

In summary, the principal response of a meandering channel to an upstream dam is reduced rates of channel migration and riparian pioneer establishment. In contrast, the principal response of a braided channel to an upstream dam is a burst of narrowing and riparian pioneer establishment. Over the long term, narrowing and pioneer establishment along the formerly braided stream will slow as a narrower equilibrium width is approached. Pioneer forests will decrease, and the subsequent ecological succession will be similar to that in a formerly meandering channel (Johnson 1998). Such declines of pioneer species are now being observed along formerly braided rivers whose flow was altered in the 19th century, such as the North Platte, South Platte, and Arkansas rivers in Wyoming and Colorado (Crouch 1979, Snyder and Miller 1991, Miller et al. 1995). In some cases, the time necessary for this decline to occur may be longer than the life of the dam.

Physiographic and Climatic Controls on Channel Morphology

Because channel morphology controls the response of a stream and riparian forest to an upstream dam, regional patterns of response to dams should be related to patterns in the environmental factors that control channel morphology. The principal factors governing channel morphology in the Great Plains are sediment supply and flow variability. Braiding is favored by a sediment supply rich in non-cohesive, easily transported sand and coarse silt, and poor in the clay and cobbles that build resistant banks; meandering is favored by sediment supply rich in clays (Lane 1957, Leopold and Wolman 1957, Schumm 1960, Osterkamp and Hedman 1982). Although some braided channels in the Plains are known to be associated with sand dunes (e.g., Osterkamp and Hedman 1982, Smith and Smith 1984), there have been no studies relating the overall spatial distribution of braided and meandering channels to surficial geology in the Great Plains.

Four broad classes of surficial sediment deposits dominate the study region: glacial deposits, aeolian (wind) deposits, ancient fluvial deposits, and locally derived deposits (Hunt 1979, Figures 1 and 2). Be-

Figure 1. Physiographic divisions and state names for the Great Plains Physiographic Province and portions of the Central Lowlands Physiographic Province in central United States (redrawn after Fenneman and Johnson 1946).

cause erodibility and particle-size distribution vary among these classes, they should influence the regional pattern of braided and meandering streams. This influence is complicated, however, by the fact that the sediment carried by a river at a given point may be derived from sources far away in the watershed.

The glacial deposits in the northeast (Figure 2) are mostly ice-laid till and lake-bed sediments of Wisconsin age (the most recent continental glaciation). Till is a poorly sorted, compacted sediment including considerable amounts of silt and clay; lake-bed sediments are also rich in clay. Meandering channels should predominate on these glacial deposits for three reasons. First, the abundant clay builds cohesive streambanks. Second, the compacted, poorly sorted till yields relatively small amounts of the sand and coarse silt that promote braiding. Third, the low slopes in this recently deglaciated region are not conducive to braiding.

The aeolian deposits (Figure 2) are unconsolidated sand dunes and loess hills mostly of Wisconsin and post-Wisconsin age. Aeolian deposits are most abundant in and near the High Plains and are dominated

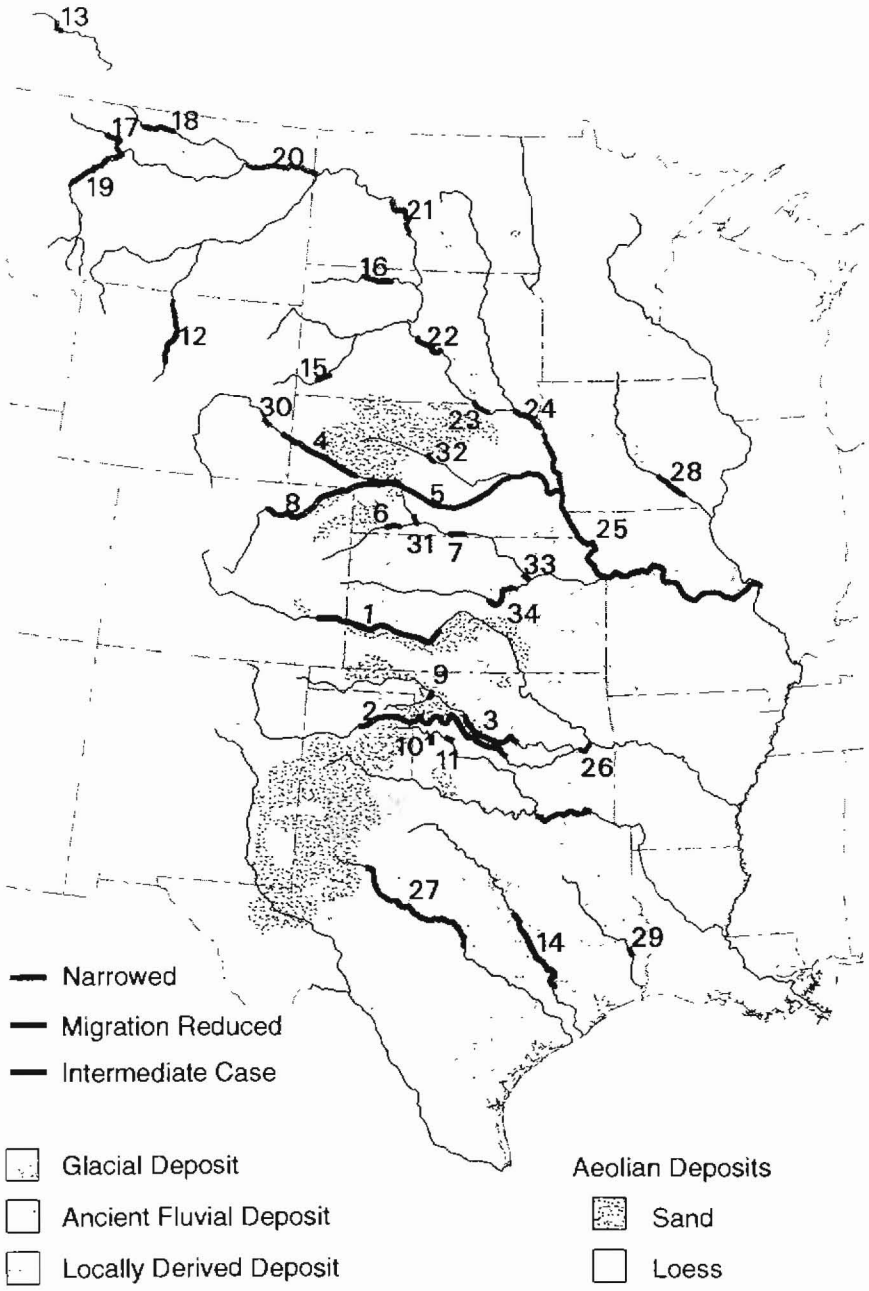

Figure 2. Downstream effects of dams in central United States. Surficial geology is redrawn after Hunt (1979). Numbers refer to stream reaches described in Table 1. Red lines indicate streams that narrowed by more than 35%. Blue lines indicate streams whose channel migration rate was reduced. Green lines are intermediate cases as described in Table 1.

by sediment blown out of the flood plains of the major rivers by winds from the west (Osterkamp et al. 1987, Madole 1995). Sand dunes contain little clay and abundant sand, a combination that produces the non-cohesive banks and abundant bedload necessary for braiding. Loess hills include abundant coarse silt, which promotes braiding, as well as some fine silt and clay, which promote meandering.

The ancient fluvial deposits (Figure 2), including the Ogallala Formation, are cemented deposits of Pliocene age and older dominated by sand and gravel. Where the sands released from these deposits are abundant, braiding should be promoted.

The locally derived deposits consist of relatively thin mantles of clay, silt, and sand derived from the disintegration of local sedimentary sandstone or shale. The abundance of clay and sand are related to the predominance of shale or sandstone in the watershed. As a result, both meandering and braided channels should occur.

High flow variability favors braiding by retarding the development of stable banks (Osterkamp 1978). Flow variability increases with aridity (Wolman and Gerson 1978). In the Great Plains, rainfall decreases from east to west, and evaporation increases from north to south (U.S. Department of Agriculture 1981). Therefore, climate should favor braided channels in the south and west and meandering channels in the north and east. Because ground-water discharge and montane snow-melt produce peak discharges of longer duration than rainfall, rivers dominated by these water sources should have low flow variability, which should favor meandering channels.

Approach

Since the response of a bottomland forest to water management is controlled by channel morphology, the regional pattern of that response should be influenced by the climatic and geologic factors that determine channel morphology. Channel-narrowing and transient pioneer forest expansion should be the dominant response to upstream dams in regions where wide, shallow braided channels predominate; conversely, reduced channel migration rate and decline of pioneer forest should be the dominant response to dams in regions where meandering channels predominate. Furthermore, the regional distribution of meandering and braided channels should be related to surficial geology and flow variability. We reviewed historical studies to document the regional pattern of channel and forest change and then carried out a spatial analysis of channel geometry data in the Great Plains to relate regional patterns in channel width to flow variability and physiography.

METHODS

We limited our analysis to an area of the central United States including the Great Plains Physiographic Province and two adjacent Sections of the Central Lowlands Physiographic Province, the Western Lakes Region and the Dissected Till Plains (Fenneman and Johnson 1946, Figure 1). These boundaries take advantage of relatively abundant data in the area and simplify the analysis by limiting it to relatively low-gradient channels. Rivers in this area generally flow to the east or southeast. The headwaters of the largest rivers are west of the area in the Rocky Mountains.

We reviewed the literature on downstream effects of dams in the Great Plains to document regional patterns in the response of channels and riparian forests. We classified the pre-dam condition as either braided or meandering and characterized the downstream response to the dam as a decrease in channel width or a reduction in the rate of channel migration; in some cases the response was characterized as intermediate. Because many studies include data on channel width, we were able to use a quantitative threshold (35% decrease in width) to determine whether important narrowing had occurred. Because data on channel migration are less commonly reported, we had to rely on the conclusions of the original authors to determine whether an important reduction in migration rate had occurred.

To explore regional patterns in channel morphology, we re-examined the data of Osterkamp et al. (1982), the largest data set on channel geometry of Great-Plains streams. The authors related discharge data from long-term USGS gages to channel geometry measured between 1976 and 1980. They avoided stations subject to extreme modification by water management. Where a gage was in an atypical location, such as a bridge, channel measurements were carried out at a more representative location nearby. Channel width was measured at the active channel reference level, which approximates the width at the mean annual discharge (Osterkamp and Hedman 1982).

We used channel width, normalized to mean annual discharge, as a surrogate for channel pattern. Width and discharge data were log-transformed to reduce positive skewness (Leopold and Maddock 1953, Osterkamp and Hedman 1981, 1982, Kolberg and Howard 1995). Ordinary Least Squares regression was applied to the transformed data to fit the linearized power function

$$\log(w) = a + b*\log(Q)$$

where w is channel width, Q is the mean annual discharge, and a and b are constants. We characterized a channel as wide if its measured width was more than 20% greater than that predicted by the regression for a stream of the same mean annual discharge (Osterkamp 1978). Wide channels are assumed to be more likely to be braided and more susceptible to narrowing.

We characterized flow variability in a similar way. For each site, we calculated the ratio of the ten-year flood to the mean annual discharge. We applied Ordinary Least Squares regression to log-transformed data to fit the linearized power function

$$\log(Q_{10}/Q) = c + d*\log(Q)$$

where Q_{10} is the ten-year recurrence-interval flood calculated by Osterkamp et al. (1982). We characterized flow variability as high (low) if Q_{10}/Q was higher (lower) than the value predicted by this regression. We superimposed information about channel width, flow variability, and stream responses to dams on maps of the surficial geology and physiographic divisions of the United States (Fenneman and Johnson 1946, Hunt

1979, Wharton 1995) using Arc/Info version 7.1.1 Geographical Information System (Environmental System Research Institute Inc. 1992, 1997) and a UNIX operating system.

RESULTS

We found 35 studies of channel and forest change downstream from dams in the study area (Table 1, Figure 2). There were eleven cases of channel-narrowing that exceeded 35% and thirteen cases of reduced channel migration rate. There were eleven intermediate cases: one case where both channel-narrowing and reduced migration rate occurred; nine cases where channel-narrowing did not occur but there was no information on migration rate; and one case where neither channel-narrowing nor a reduction in channel migration rate occurred. The effect of the dam was strongly related to the channel morphology prior to dam construction. Nine of the eleven channels that narrowed were braided prior to dam construction, and all thirteen channels that experienced a reduction in migration rate were meandering. The one channel that experienced both effects, the Missouri River below Big Sioux River, Iowa, was a formerly mobile channel with many islands that was intermediate between the braided and meandering conditions.

There was a strong spatial pattern in the distribution of the two syndromes of channel change downstream from dams. All cases of narrowing of braided channels occurred south of the Nebraska-South Dakota border, and almost all were in or near the High Plains Region (Figures 1, 2). All cases examined north of the High Plains were meandering channels that experienced a reduction of migration rate. East of the High Plains, cases of narrowing graded into intermediate cases and one case of reduced channel migration rate.

Streams in the Great Plains examined by Osterkamp et al. (1982) varied in mean annual discharge from 0.004 to 1370 m^3/s, varied in width from 0.76 to 350 m, and varied in flow variability (the ten-year discharge divided by the mean discharge) from 2.0 to 5,110. These data demonstrate the well-known correlations between width and mean annual discharge (Figure 3) and between flow variability and mean annual discharge (Figure 4). Ninety-four of 286 channels were characterized as wide (more than 20% wider than predicted by the regression of width vs. discharge).

High flow variability was only weakly associated with channel width. Where flow variability was high, 53 (36%) of 147 channels were wide. Where flow variability was low, 28 (24%) of 109 channels were wide.

Flow variability was not dominated by the west-east gradient of increasing precipitation or the north-south gradient of increasing evaporation (Figure 5). The most important influence on flow variability seemed to be the water source, which acts at a more local scale. Flow variability was low in snow-melt dominated rivers draining mountainous areas, such as the Black Hills of extreme western South Dakota and the westernmost sites in Montana and Wyoming. Flow variability was also low in streams dominated by ground-water discharge associated with the sandhills and nearby ancient fluvial deposits in Nebraska. Finally, flow variability was low in the glaciated Western Lake Region (Figure 1), which combines high precipitation, low evaporation, low gradients, and storage of water in numerous lakes.

The distribution of wide and narrow channels within the Great Plains was only weakly associated with the local sediment (Figure 6). As expected, wide channels were most abundant in areas dominated by aeolian sediment (40 of 82 channels or 49%). However, wide channels were not more abundant in areas dominated by ancient fluvial sediments (10 of 52 channels or 19%) than in areas of glacial (14 of 52 channels or 27%) or locally derived sediment (30 of 100 channels or 30%, Figure 6). Because abundant sand promotes braiding, the widest channels might have been expected in areas of aeolian sand. However, there were few channels in these areas (Figure 6), presumably because rapid infiltration of precipitation reduces surface runoff.

Consistent with patterns observed in the channel change data set (Table 1, Figure 2) wide channels were common in central Nebraska and the southern plains, and narrow channels were common in the Dakotas (Figure 6). However, channel width (Figure 6) showed some patterns that were not apparent in the channel-change data set (Figure 2). There were wide channels in the loess hills of western Iowa and in both the unglaciated and glaciated portions of eastern Montana (Figure 6). There were many narrow channels in the margins of the Nebraska sandhills, particularly near the western, northern, and southern borders of the state. Almost all of these narrow channels had mean annual discharges smaller than the median (2.04 m^3/s Figure 6); most were dominated by ground-water discharge and had low flow variability (Figure 5).

DISCUSSION

Our analysis of channel change (Table 1, Figure 2) shows that there is a regional pattern in the response of rivers to upstream dams in the Plains that is related to geologic and climatic factors known to influence channel geometry. The principal response of a braided channel is narrowing, and the principal response of a meandering channel is a reduction in the migration rate. Prior to water management, braided channels

Table 1. Downstream effects of dams on channel geometry in the Great Plains. Number refers to a labeled reach in Figure 2. Channel type indicates whether a channel was braided (B) or meandering (M) prior to flow regulation

Number	Stream	Reach Description	Channel Type	Citation
Channel narrowing by more than 35 percent (red in figure 2)				
1	Arkansas River	John Martin Dam, CO to Edwards County, KS	B	Tomellen 1984, Williams and Wolman 1984
2	Canadian River	Sanford Dam, TX to western Pottawatomie County Line, OK	B	Williams and Wolman 1984, Stinnett et al. 1988
3	North Canadian River	Canton Dam to McLoud, OK	B	Williams and Wolman 1984
4	North Platte River	Rawhide Wildlife Management Area, WY, to Lake McConaughy, NE	B	Williams 1978, Miller et al. 1995
5	Platte River	North Platte, NE to confluence with the Missouri River, NE	B	Williams 1978, Johnson 1994
6	Republican River	Trenton Dam to McCook, NE	B	Williams and Wolman 1984
7	Republican River	Harlan County Dam to Riverton, NE	B	Williams and Wolman 1984
8	South Platte River	Greeley, CO to North Platte, NE	B	Williams 1978, Johnson 1994
9	Wolf Creek	Fort Supply Dam to confluence with the North Canadian River, OK	B	Williams and Wolman 1984
10	Sandstone Creek	near Cheyenne, OK	?	Bergman and Sullivan 1963
11	Washita River	Foss Dam to Clinton, OK	M	Williams and Wolman 1984
Reduced channel migration rate (no channel narrowing; blue in figure 2)				
12	Bighorn River	Boysen Dam to Big Horn Lake, WY	M	Akashi 1988
13	Bow River	Calgary to confluence with Highwood River, Alberta, Canada	M	S.B. Rood, pers. comm.
14	Brazos River	Waco to Interstate 10, TX	M	Gillespie and Giardino 1996
15	Cheyenne River	Angostura Dam to Custer County, SD	M	W.C. Johnson, pers. comm.
16	Grand River	Shadehill Dam to highway 65, SD	M	W.C. Johnson, pers. comm.
17	Marias River	Tiber Dam to confluence with the Missouri River, MT	M	Rood and Mahoney 1995
18	Milk River	Fresno Dam to Havre, MT	M	Bradley and Smith, 1984, 1986
19	Missouri River	Canyon Ferry Dam to confluence with the Marias River, MT	M	M.L. Scott, pers. obs.
20	Missouri River	Fort Peck Dam, MT to Lake Sakakawea, ND	M	Williams and Wolman 1984
21	Missouri River	Garrison Dam to Lake Oahe, ND	M	Williams and Wolman 1984, Johnson 1992
22	Missouri River	Oahe Dam to Lake Sharpe, SD	M	Williams and Wolman 1984, W.C. Johnson, pers. comm.
23	Missouri River	Fort Randall Dam to Lewis and Clark Lake, SD	M	Williams and Wolman 1984, W.C. Johnson, pers. comm.
24	Missouri River	Gavins Point Dam, NE/SD to confluence with the Big Sioux River, SD/NE/IA	M	Williams and Wolman 1984, W.C. Johnson, pers. comm.
Channel narrowing by more than 35% and reduced channel migration (green in Figure 2)				
25	Missouri River	Big Sioux River, SD/NE/IA to confluence with the Mississippi, MO	M/B	Lane 1957, Funk and Robinson 1974, Hallberg et al. 1979
No channel narrowing; no information on channel migration (green in Figure 2)				
26	Canadian River	Eufaula Dam to confluence with Arkansas River, OK	?	Williams and Wolman 1984
27	Colorado River	From Lake J. B. Thomas through Runnels County, TX	M	Larner et al. 1974
28	Des Moines River	Red Rock Dam to Ottumwa, IA	?	Williams and Wolman 1984
29	Neches River	Town Bluff Dam to State road 1013, TX	?	Williams and Wolman 1984

Table 1. Continued.

Number	Stream	Reach Description	Channel Type	Citation
30	North Platte River	Guernsey Dam to 5 km downstream, WY	?	Williams and Wolman 1984
31	Medicine Creek	Medicine Creek Dam to 5 km downstream, NE	?	Williams and Wolman 1984
32	Middle Loup River	Milburn Dam to 7.4 km downstream, NE	B	Williams and Wolman 1984
33	Republican River	Milford Dam to 4 km downstream, KS	?	Williams and Wolman 1984
34	Smoky Hill River	Kanopolis Dam to Chapman, KS	?	Williams and Wolman 1984
No channel narrowing, and no reduced channel migration rate (green in figure 2)				
35	Red River	Denison Dam to Albion, TX	M/B	Williams and Wolman 1984, Whitesell et al. 1988

were most common in and near the High Plains, and meandering channels were more common elsewhere (Table 1, Figure 2), a conclusion that is consistent with observations of 60 channels in the region by Lane (1957). As a result, the principal response of rivers to upstream dams has been narrowing in the High Plains and reduction in migration rate in the northern and eastern Plains. This pattern explains apparent contradictions between conclusions of studies that focused on single rivers or small regions (e.g., Stinnett et al. 1988, Rood and Mahoney 1990) and provides a framework for predicting effects of dams in the Great Plains and elsewhere.

Pleistocene Sediment Transport and Channel Geometry

Prior to water development, large rivers tended to be braided in and near the High Plains and meandering in the northern and eastern Plains (Table 1, Figures 1 and 2). The abundance of braided rivers in an area whose surficial sediments are largely ancient fluvial deposits could be interpreted to mean that sand derived from these deposits is responsible for the braiding. This is true for some small streams. However, most of the sand in the flood plains of the larger rivers, such as the North Platte, South Platte, Arkansas, and Canadian, was eroded from the Rocky Mountains during

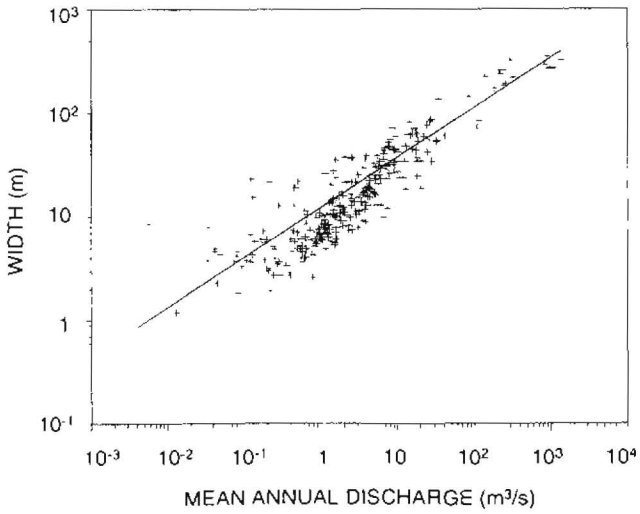

Figure 3. Active channel width as a function of mean annual discbarge for Plains streams sampled by Osterkamp et al. (1982). The line separates streams characterized as narrow from those characterized as wide (width more than 20% greater than predicted by the regression: $\log(w) = 1.01 + 0.48 * \log(Q)$).

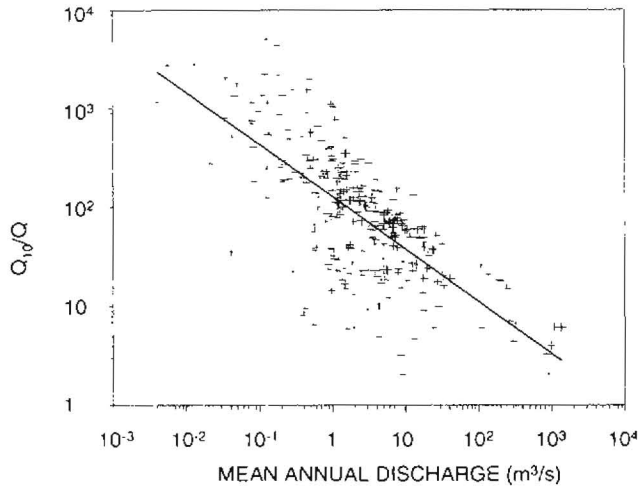

Figure 4. Flow variability (10-year flood divided by mean annual discharge) as a function of mean annual discharge for Plains streams sampled by Osterkamp et al. (1982). The line is the regression $\log(Q_{10}/Q) = 2.11 - 0.53 * \log(Q)$ and separates streams whose flow variability is characterized as higb from those whose flow variability is characterized as low.

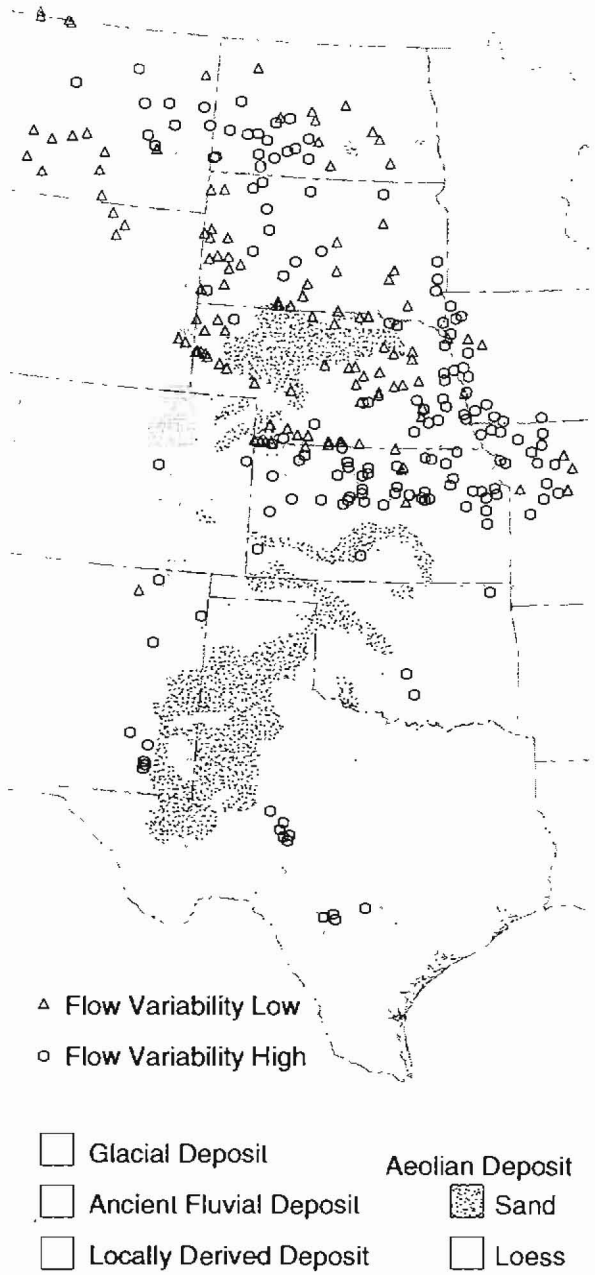

Figure 5. Flow variability and surficial geology (Hunt 1979) of Plains streams sampled by Osterkamp et al. (1982). Blue triangles (red circles) are streams with flow variability less than or equal to (greater than) the value predicted by the regression between flow variability and mean annual discharge (Figure 4).

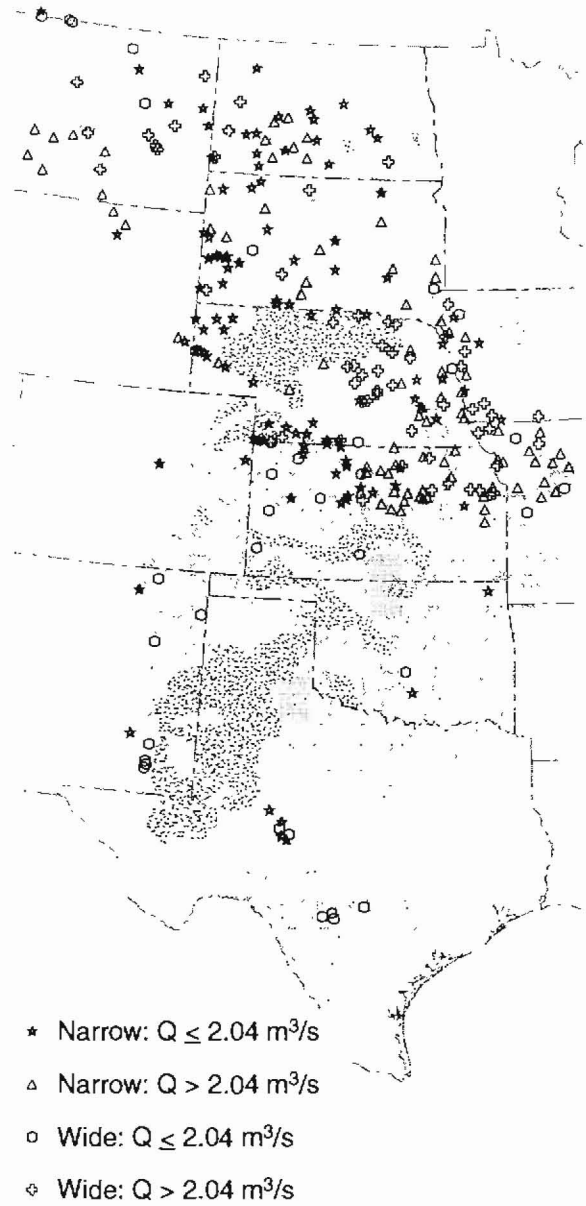

Figure 6. Channel width and surficial geology (Hunt 1979) of Plains streams sampled by Osterkamp et al. (1982). Blue stars (triangles) are streams characterized as narrow, whose mean annual discharge is less than or equal to (greater than) the median for all streams, 2.04 m^3/s. Red circles (crosses) are streams characterized as wide, whose mean annual discharge is less than or equal to (greater than) the median. Streams are characterized as wide (narrow) if their width is more (less) than 20% above the value predicted by the regression between width and mean annual discharge (Figure 3).

the Pleistocene (Osterkamp et al. 1987, Madole 1995). For hundreds of thousands of years during the Pleistocene, these rivers carried and sorted heavy loads of sediment. Cobbles were deposited at the base of the mountains, clay was transported out of the Plains, and sand and silt were left along the rivers and blown into the aeolian deposits now common in the region (Figure 2). The distant source of sand for rivers in the High Plains explains why they were typically braided upstream and upwind (Osterkamp et al 1987) of the ancient fluvial deposits (Figure 2).

In the glaciated northern Plains, development of ex-

tensive, well-sorted sand deposits was prevented by repeated incursions of continental glaciers, which relocated rivers and deposited poorly sorted glacial till. Along most of the rivers in this region, the smaller quantity of sand, presence of cobbles and clay, and low flow variability (Figure 5) limit the occurrence of braiding.

In the Unglaciated Missouri Plateau (Figure 1), the relative scarcity of aeolian deposits and braided channels suggests that the large rivers such as the Yellowstone and Missouri were competent enough to transport most sand and silt out of the region. This may have prevented the development of broad sandy valleys and aeolian deposits that characterize the major rivers of the High Plains.

Differences Between the Data Sets

The channel-geometry data set (Figure 6) does not show the clear regional pattern demonstrated by the channel-change data set (Figure 2) for several reasons. First, the channel-geometry data set (Osterkamp et al. 1982, Figure 6) includes streams whose mean annual discharges range over five orders of magnitude (Figure 3). Where the influence of environment on channel morphology is scale-dependent, small streams may show a different spatial pattern from large streams. This source of variability is absent from the channel-change data set (Figure 2) because it is almost entirely limited to large streams.

For example, streams with watersheds in sandy areas of the High Plains in Nebraska have an abundant supply of bed material, which should promote a wide, braided channel (Figure 6). On the other hand, infiltration of rain in these sandy watersheds is so rapid that runoff is minimal, streamflow is dominated by ground-water discharge, and flow variability is low (Figure 5, Osterkamp and Hedman 1982), which should promote a narrow channel. In the large streams (mean annual discharge above the median), the effect of abundant bedload predominates and channels are wide and braided (Figure 6). In the smaller streams, the effect of low flow variability predominates, and channels are narrow (Figure 6, Osterkamp and Hedman 1982). Because the channel-change data set (Figure 2) is dominated by large rivers, it shows in Nebraska mostly rivers that were braided prior to water management.

A second factor obscuring regional pattern in the channel-geometry data set is the late date of sampling, 1976–1980, which followed construction of most dams in the Plains. Therefore, patterns of channel width due to geologic and climatic factors are confounded with patterns in channel width caused by flow regulation and land management. Water development has been more intense in the southern Plains than in the northern Plains (Hitt 1984), a factor that has reduced the regional contrast in channel width.

A third contrast between the data sets is a difference in sampling bias. Whereas analyses of downstream effects of dams (Table 1, Figure 2) have tended to gravitate toward the extreme or archetypal cases, Osterkamp et al. (1982) avoided such rivers because of their interest in relatively undisturbed channels. For example, there are no samples in the data set of Osterkamp et al. (1982) from the regulated North Platte and Arkansas rivers.

A fourth factor is the use of the width-discharge relation as an indicator of susceptibility to narrowing. Several factors can influence channel width without affecting the susceptibility to narrowing. For example, because of ice scour, channels in Alberta tend to be larger for their discharge than channels in the United States (Smith 1979). This greater width does not make Canadian channels more susceptible to narrowing downstream from dams unless the dams are operated to reduce ice effects. In addition, as gradient decreases, velocities decrease and channel width increases; the resulting large width of some very low-gradient channels does not render them more susceptible to narrowing.

Although the channel-change data set indicates that narrowing of braided channels was essentially limited to the vicinity of the High Plains (Figure 2), there were wide channels in the loess hills of western Iowa and in both the unglaciated and glaciated portions of eastern Montana (Figure 6). The differences between Figures 2 and 6 in western Iowa result in part because no large dams have been built in the region (Hitt 1984). Thus, although braided channels occur, the absence of major dam construction means that there has been little opportunity for downstream channel-narrowing. In addition, soil loss resulting from intensive cultivation of steep slopes apparently increased bed sediment loads in these streams prior to collection of channel-geometry data (U.S. Department of Agriculture 1981, Osterkamp et al. 1982). Some of these channels appear to be near a transition between braided and meandering conditions. High regional slopes and high flow variability favor braiding in these streams. They also have an abundant source of coarse silt, which is transported largely as bedload but is cohesive enough to stand in vertical banks. Channel-widening related to increased erosion from agricultural lands was common in the eastern plains in the early 1900s, although this widening has been reversed by soil conservation practices in many cases (Knox 1977, Johnson et al. 1980, Trimble and Lund 1982, Magilligan 1985).

In eastern Montana, several wide channels are present (Figure 6) even though the only reported response

to dam construction in the area has been reduced migration of meandering channels (Figure 2). The channel-morphology data of Lane (1957) confirm that strongly braided channels are uncommon in this area, which is consistent with the lack of large aeolian deposits (Figure 2). The streams in this area that have the greatest tendency toward braided conditions are those with high flow variability whose watersheds contain loosely consolidated sandstones that provide abundant bedload. Examples include the Powder, Tongue, Yellowstone, and possibly Bighorn rivers (Hunt 1979). These rivers often develop multiple channels; however, the channels are fewer and shift less rapidly than the classic braided channels of the High Plains; in addition, the channels often migrate across a broad forested bottomland. A dam on such a river would be expected to lead to both a reduction in channel migration rate and a significant burst of narrowing. The channel-change data set (Figure 2) includes only one example from these four rivers: Boysen Dam on the Bighorn River has reduced channel migration rate and caused moderate narrowing of less than 35% of the original channel width (Table 1; Akashi 1988).

Any coarse-scale analysis of pattern requires simplifying assumptions. Understanding the limitations of those assumptions is important in interpreting and generalizing the results. A central assumption of our analysis is that Great-Plains channels all fall along the braided-meandering continuum. Although most channels in the region can be characterized as braided or meandering, some cannot (Schumm 1977, Nanson and Croke 1992). An important class of exceptions is relatively narrow channels that migrate little because they are constrained by bedrock or sediment particles too coarse to be easily moved by the stream. This class of channels dominates mountainous areas; such channels are less numerous in the plains but include important examples such as incised channels within the Llano Estacado of New Mexico and Texas and montane channels in the Black Hills of South Dakota. Because width of constrained channels can be influenced more by degree of confinement than by sediment supply or flow variability, such channels are not adequately accounted for by our characterization based on width (Figure 6). Along constrained channels, a reduction in peak flows may have little effect on width or migration rate; however, riparian pioneer forests may still be affected. For example, along a constrained section of the Missouri River flowing through the Missouri Breaks in Choteau, Fergus, and Blaine counties, Montana, riparian pioneers occur only in a discontinuous narrow band along the channel and usually become established following large floods that deposit bare moist sediment at positions high enough on the bank to avoid subsequent scouring by ice jams and floods (Scott et al. 1997, Auble and Scott 1998). Scott et al. (1997) have argued that maintenance of the present forest depends upon maintaining the magnitude of peak flows with a recurrence interval of 9 years or greater.

Factors Influencing Forest Abundance

Channel-narrowing as a result of water management has led to expansion of pioneer riparian forests in the southwestern Plains where braided channels were formerly common. On the other hand, in the northern and eastern Plains, losses of bottomland forest due to land-clearing and other factors have been greater than any gains from channel-narrowing. In the remaining forests, pioneer species are being replaced by smaller, shade-tolerant species (Friedman et al. 1997).

Several factors other than dams have greatly influenced regional abundance of forest in the Great Plains since settlement. Shrubs and trees have been planted on uplands to reduce wind erosion in agricultural and residential areas (Read 1958). Large areas of bottomland forest in the Great Plains have been cleared for agriculture, mostly along formerly meandering channels in the northern and eastern Plains (Bragg and Tatschl 1977, Friedman et al. 1997). Ground-water pumping has been associated with decreased streamflows and tree mortality along many Great Plains streams (Jordan 1982, Kromm and White 1992). Reductions in fire frequency beginning around the time of settlement in the mid-1800s allowed westward advancement of trees (Bruner 1931). Floods, droughts, and intrinsic processes of channel change have caused extensive changes in channel geometry and riparian forests (Albertson and Weaver 1945, Schumm and Lichty 1963, Friedman et al. 1996, 1997). Reservoir construction has probably inundated more than 5% of the length of major streams in the United States (Brinson et al. 1981) and eliminated many bottomland forests associated with those streams (Anderson 1971); however, as reservoirs fill with sediment, some new land suitable for tree establishment is created.

Ecosystem Effects

Riparian forests are important animal habitat in landscapes that contain few other trees. In the Great Plains, the proportion of vertebrates found mostly in riparian areas is far greater than the proportional representation of these areas in the landscape (Brinson et al. 1981); therefore, the regional pattern in the effect of dams on downstream forests has implications for related plant and animal communities in the Plains. The balance among the many factors influencing forest change varies from region to region within the Plains. For example, in eastern Colorado, trees were so scarce

prior to settlement that explorers traveling the corridor of the South Platte River typically had to burn bison dung for fuel (Frémont 1988). Flow regulation along the South Platte and Arkansas rivers led to development of continuous riparian forests along these formerly braided channels (Williams 1978, Johnson 1994, Figure 2). Along many of the smaller streams including the Arikaree and Republican rivers and Bijou and Kiowa creeks, extreme floods in 1935 and 1965 led to channel-widening and then post-flood narrowing and forest development, greatly increasing the area of forest (Friedman et al. 1997). Finally, settlement of the area included extensive tree-planting in shelterbelts and near homesites. These increases in forest have greatly changed the fauna of the region. Almost 90% of the 82 breeding bird species predictably present each spring on the steppe of eastern Colorado were not present in 1900 (Knopf 1986). The new species are typically habitat generalists of forest edges that have expanded into the Plains as forests have expanded (Finch 1989). Many animals specializing in grasslands are in decline, in part because they are susceptible to predation and competition from animals that use trees (Knopf 1992, Burger et al. 1994).

Increases in forest species in eastern Colorado are contrasted by decreases in much of South Dakota. Prior to settlement, the meandering Missouri River in South Dakota supported broad, continuous riparian forests. Most of these forests have been removed as a result of land-clearing and inundation by reservoirs, and pioneer species on the remaining flood-plain forest have decreased as a result of reduced channel migration (Johnson et al. 1976). These forest declines have been only partially offset by tree-planting on uplands, and decreases in some forest vertebrates have resulted (Anderson 1971, Brinson et al. 1981).

The processes of channel change and forest development are ongoing. The burst of channel-narrowing and tree establishment following dam construction along formerly braided streams is completed after several decades when the channel approaches a new narrower equilibrium width (Johnson 1998). Over time, the riparian pioneers are replaced by grasses or shade-tolerant trees. Thus, over the long term, the response of formerly braided channels to upstream dams approaches that of formerly meandering channels. Construction of dams in the United States has decreased since the 1970s. In the next several decades, the pioneer forests established downstream from dams in the High Plains will experience a decrease in regeneration as channel-narrowing slows. The inevitable decline of these forests will be exacerbated by continuing drawdown of the High Plains aquifer (Luckey et al. 1988). These changes in the forest can be expected to influence populations of many other organisms in the region.

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