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ADJUSTMENT OF RIPARIAN VEGETATION TO RIVER REGULATION IN THE GREAT PLAINS, USA

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Abstract: The Missouri River and the Platte River provide opposite examples of the way riparian vegetation responds and adjusts to regulation by dams and diversions. *Populus-Salix* woodland has expanded rapidly into Platte River channels, while it has failed to regenerate in gaps between reservoirs along the upper Missouri River. This divergent response is the result of different geomorphologies and water-use patterns. The Platte River is a braided-type stream with a significant portion of its flow diverted for cropland irrigation. The Missouri is a meandering-type stream with low irrigation usage. I developed a graphical model that characterizes the different ways that riparian vegetation has adjusted to regulation. The model identifies two time periods: pre-regulation and post-regulation adjustment, with the latter divided into phase 1 and phase 2 subperiods. In the pre-regulation period, woodland composition shifts according to weather extremes and climate change. During phase 1, braided rivers adjust by channel-narrowing and expansion of pioneer woodland (*Populus-Salix*), while meandering rivers cease meandering. During phase 2, after major geomorphic adjustments are complete, both types of rivers show sharp declines in pioneer woodland. Replacement communities in the new equilibrium (post-adjustment period) will be dominated by later successional woodland or grassland species. Geomorphic factors of importance to vegetation establishment adjust relatively quickly (decades), but the subsequent adjustment of vegetation through succession is relatively slow (century or more).

Key Words: riparian, vegetation, river regulation, *Populus, Salix*

INTRODUCTION

The individuality among rivers in their transient responses to streamflow regulation suggests that vegetation will adjust uniquely by reaching different equilibria at different rates. Different reaches of a regulated river can be in different phases of adjustment, and in any single reach, vegetation and other biological variables may experience a complex sequence of changes during the adjustment period (Petts 1987). Also, the many vegetation and hydrogeomorphic attributes of rivers respond and adjust at widely varying rates. Shorter readjustment times (within a decade after dam closure) are expected for sediment load, hydrology, floodplain vegetation, and water quality, while channel substrate, aquatic plants, channel form, and benthic invertebrates are expected to readjust more slowly, from 5 to 100+ years (Petts 1984).

Detection of adjustment of riparian vegetation to regulation requires three types of data: (1) pre-regulation vegetation and channel conditions, (2) transient response following alteration of flow and sediment supply, and (3) new vegetation composition after adjustment. These correspond to the equilibrium state 1, transient state, and equilibrium state 2 of Petts (1987).

Vegetation and environment in the pre-development river (data type 1) are used as benchmarks from which to compare post-development rates and direction of change. In the United States, the General Land Office (GLO) survey notes and maps provide useful information because river channels were usually measured and mapped, witness trees identified and measured, and notes made regarding general vegetation and environment (Stearns 1949, McIntosh 1962, Johnson et al. 1976, Bragg and Tatschl 1977, Grimm 1984, Johnson 1994). For large rivers such as the Missouri, detailed navigational maps of channels and locations of wood supplies often are available (Bragg and Tatschl 1977, Johnson 1992). Other sources assist in vegetation reconstruction, including personal diaries and photographs; however, these can be misleading (Russell 1981, 1983).

Transient responses (data type 2) can be determined from a time series of aerial photographs and maps (Turner 1974, Johnson et al. 1976, Bragg and Tatschl 1977, Nadler and Schumm 1981, Decamps et al. 1988, Johnson 1994). The most discernable changes are channel meandering rates/patterns and the area and distribution of vegetation. Substitution of time for space is widely used to detect transient changes associated with flow alterations (Everitt 1968, Johnson et al. 1976, Scott et al. 1997). Monitoring of recruitment can identify causes of demographic shifts (McBride and Strahan 1984, Johnson 1994).

Studies using these methods have identified three transient responses to regulation by North American rivers in arid and semi-arid climates. First, the historically-dominant *Populus* and *Salix* woodlands are failing to regenerate on dammed, low gradient, meandering-type rivers such as the Missouri and its upper watershed tributaries (Johnson et al. 1976, Bradley and Smith 1986, Rood and Mahoney 1990, 1995). Reservoirs have reduced peak streamflow and slowed channel meandering and point-bar formation needed for successful *Populus* and *Salix* recruitment (Bradley et al. 1991, Scott et al. 1997).

Second, flow regulation of rivers in arid regions with alkaline soils, particularly in the Southwest, has contributed to declines in native woodlands dominated by *Populus* and to large increases in exotic arboreal species, particularly *Tamarix*. *Tamarix* has formed impenetrable thickets along dammed and diverted rivers such as the Gila and Rio Grande (Turner 1974, Everitt 1980, Turner and Karpiscak 1980, Busch and Smith 1995).

Third, flow regulation and dewatering of steeper gradient, braided rivers with climates and soils unfavorable to *Tamarix* have stimulated extensive expansion of native *Populus* and *Salix* woodlands (Crouch 1979, Schumm and Meyer 1979, Nadler and Schumm 1981). For example, *Populus-Salix* woodlands occurred on the banks and islands of the Platte River prior to water development but expanded in the middle of this century so that they now occupy approximately half of the formerly active channel of the river (Johnson 1994).

Few investigators have observed the third phase of adjustment to flow regulation—attainment of a new vegetation equilibrium (data type 3)—because too little time has passed for complete adjustment. For example, the major period of large dam and diversion construction on large rivers of the Great Plains began only 40 to 60 years ago (Stanford and Ward 1979), although irrigation development on many western rivers such as the South Platte, Colorado, and Rio Grande began much earlier (Eschner et al. 1983, Ohmart et al. 1988, Everitt 1993). Yet, new equilibria of at least some important variables may have gone undetected for lack of study at the appropriate time and spatial scales (Petts 1984). Simulation models can estimate the timing and vegetation conditions of future equilibria (Johnson 1992), including the effects of regulation on long-term, system-level impacts such as biodiversity and productivity.

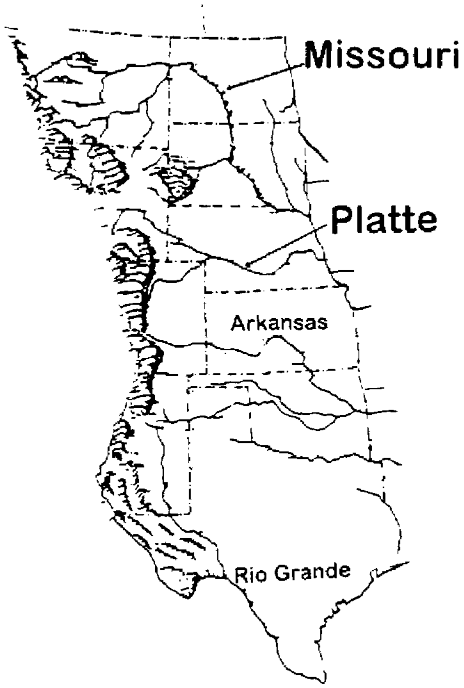

Figure 1. Large rivers in the U. S. Great Plains.

The purpose of this paper is to develop generalized graphical models of vegetation adjustment by Great Plains rivers to water regulation. The upper Missouri River (North Dakota) and Platte River (Nebraska) are discussed in detail and form the foundation of the graphical models developed. These rivers demonstrate nearly opposite responses to regulation despite having similar woodland composition, climate, and co-occurrence in the Missouri River drainage basin (Figure 1). Their responses to regulation are similar to those of many other rivers in the Great Plains and elsewhere.

PLATTE RIVER

Early Regulation Period

The first stream gages were installed in the Platte River's major tributaries, the South and North Platte Rivers, four decades after initial depletions of streamflow to irrigate cropland and pastures. Irrigation by hand-dug canals began in the late 1850s along the South Platte River near Denver, while the first stream gage was installed about 1900 at Kersey, Colorado (McKinley 1938, Eschner et al. 1983, Hadley et al. 1987). Irrigation developed later on the North Platte River (circa 1880s), and the first gage was installed at North Platte, Nebraska in the mid-1890s. Thus, the effect of initial irrigation depletions on streamflow was not captured by the early gage records.

The construction of dams postdated the start of gage records. The first large storage reservoirs were built on the North Platte River beginning with Pathfinder in 1909; there are fewer large dams and considerably less reservoir storage capacity on the South Platte River (U. S. Bureau of Reclamation 1982). Flow in the South Platte River has been augmented by transbasin diversions from the west to east slope of the Rocky Mountains (Gerlek 1977). No large dams have been constructed on the Platte River. The closest is Kingsley Dam (forming Lake McConaughy) built in 1941 on the North Platte River. Numerous diversion structures were built in the Platte River, especially in the upper (westerly) reaches.

The stream gage at Overton has the longest continuous record of flow in the Platte River (early 1930s–present); while it does not record the effects of early upstream regulation, it does capture the effects of closer and newer dams and diversions. Mean annual flow decreased sharply early in the record, remained low between the 1930s and 1960s, and has rebounded in the last several decades (Figure 2). Peak flows since the 1930s have been quite variable but approximately half of those earlier in the record (Figure 2). The prolonged period of low mean annual flow corresponds to a period that included two severe droughts (1930s and 1950s) and the filling of three large reservoirs on the North Platte River (Lake McConaughy, Glendo Reservoir, Seminoe Reservoir). Lower mean annual flow results from dewatering by irrigation (facilitated by dams), while reduced peak flow results from flow capture by reservoirs.

Cottonwood (*Populus deltoides* Marsh.) and willow (*Salix amygdaloides* Anderss., *S. exigua* Nutt.) dominated the pre-development woodlands in the Platte River (Johnson 1994). The GLO survey notes indicated that riparian woodland was dense and extensive in central Nebraska but thinned westward with increasing aridity. In western Nebraska, most trees were restricted to riverine islands, although many trees had been cut by travelers along the Oregon and Mormon Trails, and by soldiers, settlers, and railroad crews prior to the survey (Johnson 1994). Few witness trees were recorded or trees observed during the original survey of land along the Great Plains sections of the South and North Platte rivers.

The South and North Platte rivers became densely wooded with *Populus* and *Salix* between the time of the original survey (late 1800s) and the late 1930s when aerial photographs first became available. No system-wide surveys of vegetation were conducted between these periods; however, surveys completed in the North Platte River to solve legal disputes over the ownership of new islands indicated that significant woodland expansion began about the turn of the century (Johnson unpubl. data). By the late 1930s, woodland occupied about 75 percent of the channel.

Late Development Transient Changes

Woodland expansion in the Platte River lagged behind that of its tributaries. Woodland extent on late 1930s aerial photographs for the central Platte River may have been less than pre-development estimates from the GLO surveys. For example, only about 10 percent of the Platte River floodplain at Shelton, Nebraska (central Platte) was wooded in 1938 (Johnson 1994).

The *Populus-Salix* woodland expanded rapidly between the late 1930s and the 1960s. Upper Platte River channels narrowed more during this period than central Platte River reaches. For example, 93% of 1938 channel area at Cozad (upper Platte) succeeded to woodland during this period, compared to about half of the active channel area of the central Platte River reaches (Figure 3). The upper Platte reaches are closer to dams and large diversions than are the central Platte reaches.

The main transient phase of channel and woodland area change following streamflow regulation in the Platte River ended in the 1960s (Figure 3). Channel area has not significantly decreased in three subsequent decades, from the mid-1960s to the mid-1990s (Johnson 1997), although the channel has enlarged in upstream reaches. By 1995, channel area at Cozad had returned to 1951 levels.

Causes of Transient Response

Analyses indicated that the rate of channel replacement by woodland was inversely related to June streamflow (Johnson 1994). June flow controlled seedling recruitment of *Populus* and *Salix* because it coincided with the primary seed dispersal period. Historic reductions in June streamflow to fill reservoirs and to divert water to irrigate crops exposed more of the active channel allowing tree regeneration. Also, reduced post-germination flows were unable to rework the wider, pre-development channel and erode or bury the young seedlings. During the transient phase, the rate of woodland expansion was sharply higher during periods of climatic drought.

MISSOURI RIVER

Pre-Regulation Period

Significant regulation of streamflow in the upper Missouri River lagged many decades behind the Platte

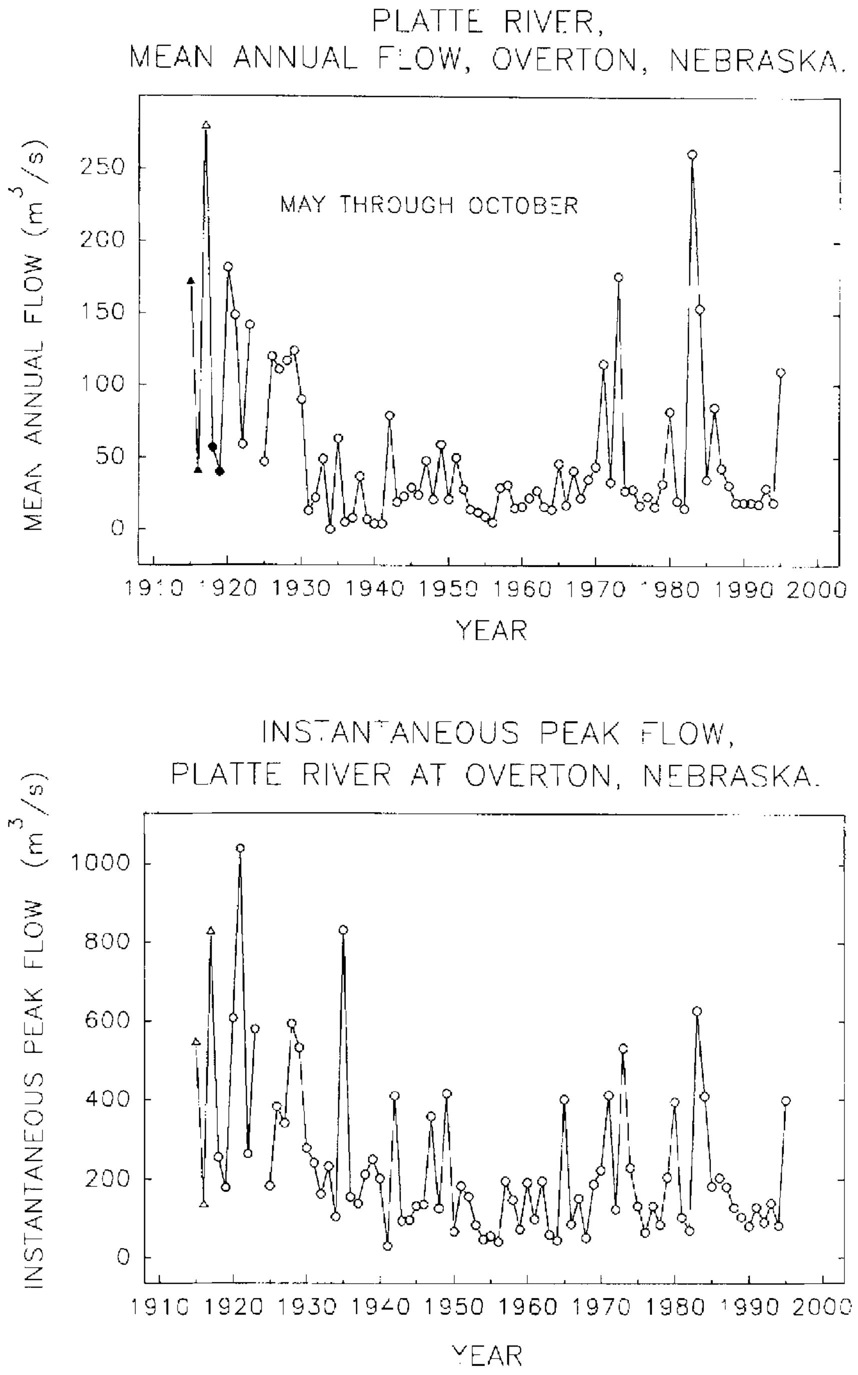

Figure 2. Historical seasonal mean and annual peak flow at Overton on the Platte River. Triangles indicate data from the Elm Creek gage (near Overton) and circles indicate the Overton USGS gage data. Darkened symbols denote years with incomplete data from May through October. No data were available for 1924.

River. Changes in flow were not apparent until after the large dams were built in the 1950s and 1960s on the upper Missouri River in the Dakotas. Oahe Reservoir (South and North Dakota) alone eliminated over 123,000 ha of riparian and floodplain lands (Hesse 1996). Floodplain and forest remnants still exist in gaps between reservoirs.

The hydrograph at Bismarck (below Garrison Dam completed in 1953) shows that dams have greatly reduced peak flow but not total annual flow (Figure 4). Between 1928 and 1953, about two-thirds of the annual peak flows at Bismarck exceeded 2,500 cms; since 1953, no peak has exceeded 2,500 cms. Reily and Johnson (1982) showed that the dams have strong-

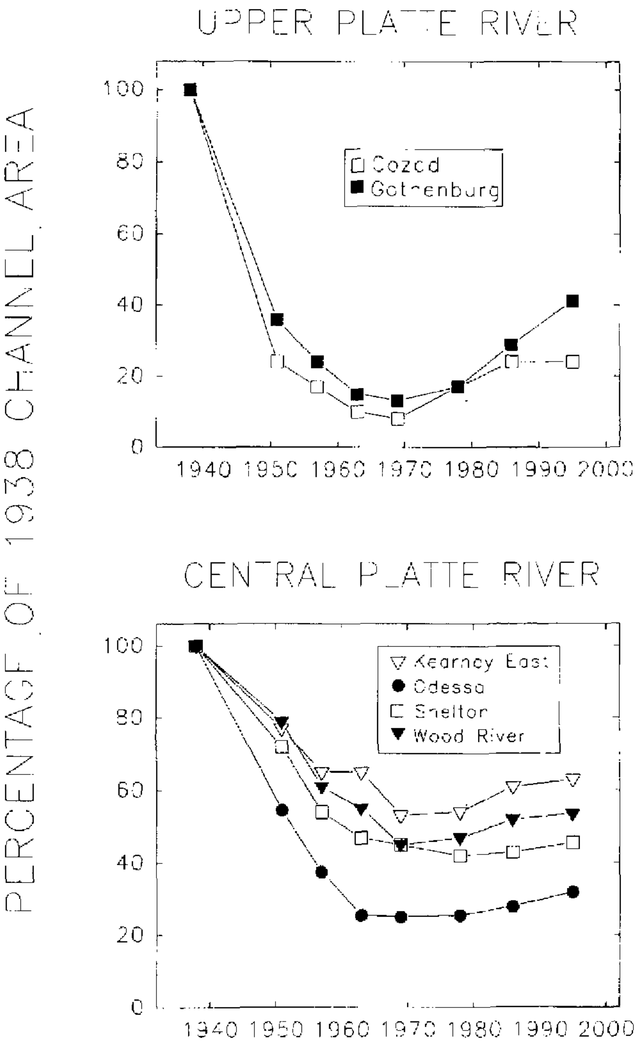

Figure 3. Changes in active (unvegetated) channel area for reaches in the upper and central Platte River. Starting channel area in 1938 was set equal to 100.

ly changed seasonal flow patterns; peak flows now occur in winter instead of in spring, and minimum flows occur mainly in spring and fall instead of in winter.

In contrast to the more arid upstream sections of the Platte River, the Missouri River floodplain was well-forested prior to settlement. Approximately three-quarters of the middle Missouri River floodplain was forested at the time of settlement, with the remaining one-quarter comprised of wetlands, grasslands, and shrublands (Hesse 1996). Almost half of the original forest along the upper Missouri River was early-successional *Populus-Salix* forest <40 years old (Johnson 1992). The other half included older *Populus-Salix* forest (40–80 years old), transitional forest (80–150 years old; *Populus-Fraxinus*), and equilibrium forest comprised of later successional species (>150 years old; *Fraxinus*).

Populus dominated the unregulated Missouri River floodplain because of the highly dynamic river channel (Johnson et al. 1976). Before the large dams, the river meandered rapidly across its floodplain during floods. This process deposited alluvium on the inside of river curves forming point bars, while on the opposite side, it eroded older forest vegetation. Point bars were optimal sites for *Populus* and *Salix* establishment (Moss 1938, Noble 1979, Hughes 1994).

Pioneer *Populus* forests that escaped erosion by the meandering river were replaced by later successional species including *Fraxinus*, *Ulmus*, and *Acer*, which reproduced in the understory. *Populus* and *Salix* are classic pioneer species unable to reproduce successfully in forest conditions; hence, channel meandering and point-bar formation associated with flooding were necessary to perpetuate these extensive forests on the pre-regulated floodplain.

Transient Period

Settlement changed the extent of the floodplain vegetation. By 1979, approximately 60% of the forest along the Missouri River had been cleared for agriculture in central North Dakota (Johnson 1992). Bragg and Tatschl (1977) found that floodplain forests along the middle Missouri River decreased from 76 percent of the land area in 1826 to 13 percent in 1972. Eighty percent of the floodplain was under cultivation in 1958.

Damming initiated a transient response affecting forest composition—a sharp decrease in young *Populus-Salix* forest. While almost half of the floodplain forest was of this type in the pre-development river, only approximately 5 percent was in this category in 1979, some 25 years after the closure of Garrison Dam. Most of these remaining young stands originated just after the last major flood (1952) on the upper Missouri River.

Causes of Transient Response

The primary cause of decreased *Populus-Salix* recruitment is the reduction in river meandering rates caused by lower peak flows. Johnson (1992) reported that bank erosion rates dropped from a pre-dam average of 93 ha/year to 21 ha/year during the post-dam period. Bank accretion rates (an index of point bar formation) fell from 111 ha/year to 1.3 ha/year. The product of these changes has been a locationally stable river channel with little generation of stable point bars for colonization by pioneer tree species.

CAUSES OF DIVERGENT RESPONSE

The two rivers showed strongly divergent responses to regulation. The Platte River narrowed quickly, and

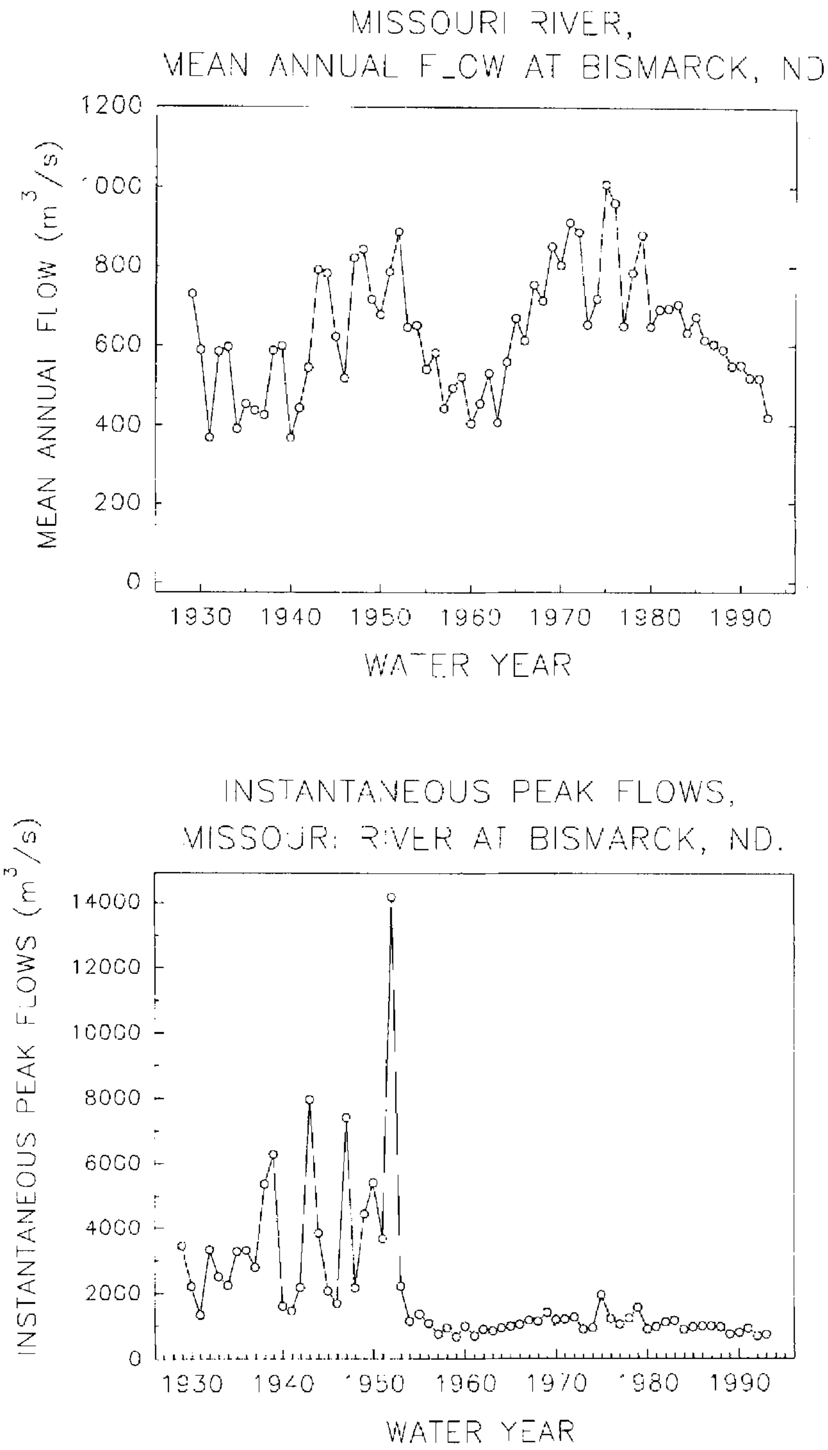

Figure 4. Historic mean annual and peak flows for the Missouri River USGS gaging station at Bismarck, North Dakota.

much of its active channel became wooded. The laterally mobile channel of the upper Missouri River stabilized and became unsuitable for the establishment of new woodland. Thus, young woodland has prospered in the Platte River but has become a thing of the past along the Missouri River.

The divergent response has several possible causes, including geomorphic type, type and magnitude of water resource development, grazing intensity, and agricultural activity. Geomorphic type is a key factor, illustrated by the opposite responses to flow regulation by the meandering Missouri River and the braided Platte River. Braided streams are relatively wide and shallow, and moderate reductions in flow cause large

Table 1. Hydrogeomorphic differences between the Missouri and Platte Rivers.

Characteristic	Missouri River	Platte River
1. Sediment size	clay to sand	sand to gravel
2. Vertical range	approx. 10–12 m.	approx. 2 m.
3. Total active channel width	narrow	wide
4. Stream gradient	gentle (0.00016 m/m)	steep (0.00125 m/m)
5. Average depth	approx. 12 m.	less than 1 m.

reductions in water width and small decreases in depth (Table 1, Figure 5). The proportion of the channel available for plant colonization is highly sensitive to flow.

Meandering rivers inside their normal banks, however, are markedly deeper and narrower than braided rivers (Table 1, Figure 5). Except at flood (overbank) stage, large changes in flow translate into large changes in depth and small changes in water width. Most permanent vegetation is located on the floodplain outside the channel because the large vertical rise in river stage during floods allows little successful in-channel plant establishment, except on the inside of river curves away from the thalweg.

High flow events are extremely important channel-forming processes in both rivers, but they affect vegetation differently. In the Platte, high flows prohibit tree recruitment and maintain wide channels, whereas high flows in the Missouri create geomorphic action and channel movement needed for the regeneration of riparian vegetation.

The rivers also differ in the type and magnitude of water development and use. While both river systems are dammed, the Missouri River reservoirs are operated to control floods, provide hydroelectric power, and support recreation. Little water from the Missouri in the Dakotas is used for cropland irrigation. In contrast, a large portion of the Platte River is diverted for cropland irrigation. Thus, the Platte has experienced both a cut in peak flows and in total annual flow, while the Missouri River has experienced only reduced peak flows.

TIME TO NEW EQUILIBRIUM

Petts (1987) stated that vegetation quickly readjusts to a new equilibrium after damming, possibly within

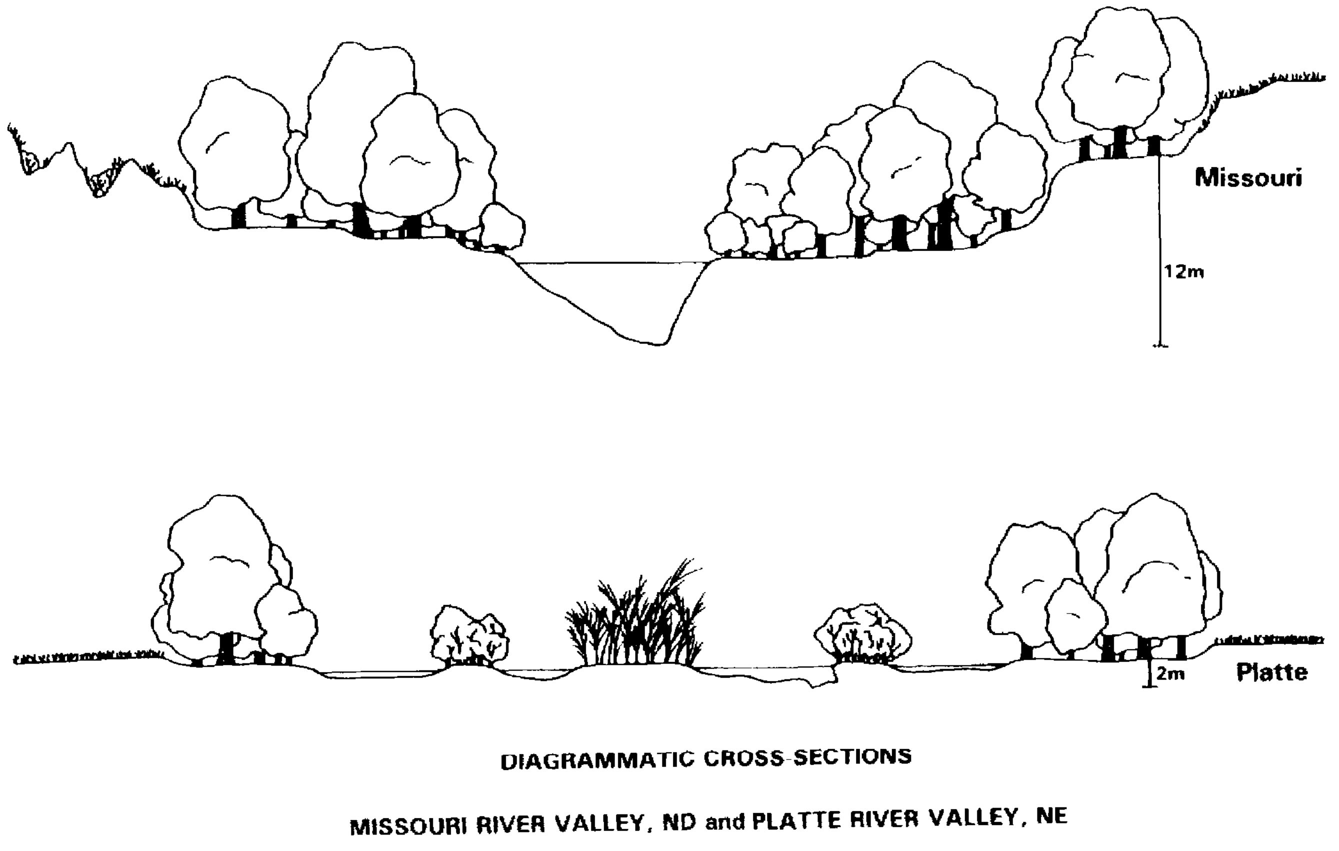

Figure 5. Diagrammatic cross-section of the Missouri River and Platte River valleys showing distribution of channels and floodplain vegetation.

10 years. Evidence indicates otherwise for the Platte and Missouri rivers. The path or trajectory to equilibrium occurs in two phases. The initial transient response of vegetation is triggered by geomorphic changes in channel structure and dynamics. For the Platte, this phase, involving channel narrowing and woodland expansion, was complete after about 3 decades. For the Missouri, locational stability of the channel and regeneration failure of pioneer trees was virtually immediate.

The species composition of neither riparian landscape, however, would be in equilibrium at the end of phase 1. Thus, a second level of change (phase 2) will occur, during which vegetation succession takes place. Time to reach compositional equilibrium (steady-state mosaic—Bormann and Likens 1979) will be much longer than in phase 1. These changes are less obvious than are changes in channel morphology and woodland area (phase 1). Nonetheless, compositional shifts triggered more by autogenic (phase 2) than by allogenic processes (phase 1) strongly affect landscape processes such as biodiversity, energy flow, and nutrient cycling (Malanson 1993). While the allogenic processes such as sedimentation, scouring, and flooding during phase 1 differ markedly between the rivers, the autogenic processes of phase 2, including improved soil fertility and a more mesic understory environment, will be quite similar. Both rivers have similar woodland vegetation and successional trajectories; *Populus deltoides* and *Salix amygdaloides* are dominant pioneer species replaced over time by later successional genera such as *Fraxinus, Ulmus, Acer,* and *Celtis.* Diversity of these later taxa decreases westward across the Great Plains (Little 1971).

In the future, both rivers should show a strong decline in the proportion of pioneer forest occupying the floodplain. Model calculations for the Missouri River indicate that the pre-dam dominance of the floodplain by *Populus* and *Salix* cannot be mantained under the current extremely low meandering rate (Johnson 1992). A new post-dam equilibrium dominated by later successional species (primarily *Fraxinus*) would be reached about 150 years after dam closure. Some *Populus-Salix* forests will persist, however, but as a narrow gallery forest near the channel, rather than as extensive bottomlands, as they have occurred historically. These projections do not consider the effects of land clearing or forest harvesting that may occur in the future.

For several reasons, a new equilibrium on the Platte River will be reached more quickly than on the Missouri, but the final composition is less certain. *Populus* appears to be shorter-lived along the Platte, probably because of the coarser, droughtier, and less fertile soils. Floodplain soils of the Platte River contain no clay and little silt; soils of the Missouri River floodplain are highest in clay and silt (Johnson et al. 1976). Hence, the succession to later species may be faster than along the Missouri, possibly within 75–100 years instead of 150 years. Certainly, *Populus* and *Salix* will remain as significant species as small areas of the wooded floodplain are eroded and new sandbars form periodically after high flow periods (Johnson 1997). However, as along the Missouri, these pioneer tree populations, occurring along active channel margins and on small islands, will constitute only a small proportion of the floodplain area.

The larger question is what communities will replace the extensive *Populus-Salix* woodland that regenerated in the Platte River during phase 1 of the adjustment period. Since the bulk of these woodlands has little chance of being eroded, they will age in place. These woodlands mostly originated in the 1940s and 1950s and therefore are now mid-way through succession. The occurrence of understory trees of later successional species provides clues into the compositional future of these woodlands, once *Populus* and *Salix* senesce and die as they are already doing along the South Platte River in Colorado (Snyder and Miller 1991). Currently, *Juniperus virginiana* L., *Ulmus americana* L., *Fraxinus pennsylvanica* Marsh., *Acer negundo* L., and *Acer saccharinum* L. dominate the sapling and small tree layer in these Platte River woodlands. At this time, however, these understory trees are quite scattered and may not form a relatively continuous canopy once the pioneer trees are gone. While succession in these forests has not been studied, indications are that relatively open-canopied forests with shrub-dominated mid-stories may develop. The more arid climate farther west along the Platte (and the droughty soils) may not support succession to forest but rather succession to grassland or to grassland/shrubland admixtures as occurs along other Great Plains rivers (Boggs and Weaver 1994, Friedman et al. 1997). Thus, the structure, composition, and biodiversity of the woodlands after phase 2 adjustment will differ markedly from those that initially colonized the formerly active channel of the Platte River during the middle part of this century.

NEW ADJUSTMENT MODEL

A grapical model expanded from Petts (1987) is proposed to characterize the response of riparian vegetation to the regulation of Great Plains rivers. The model integrates three vegetation (response) variables: proportion of the floodplain vegetated, overall vegetation composition (pioneer vs. mature), and composition of mature vegetation (woodland vs. grassland/shrub).

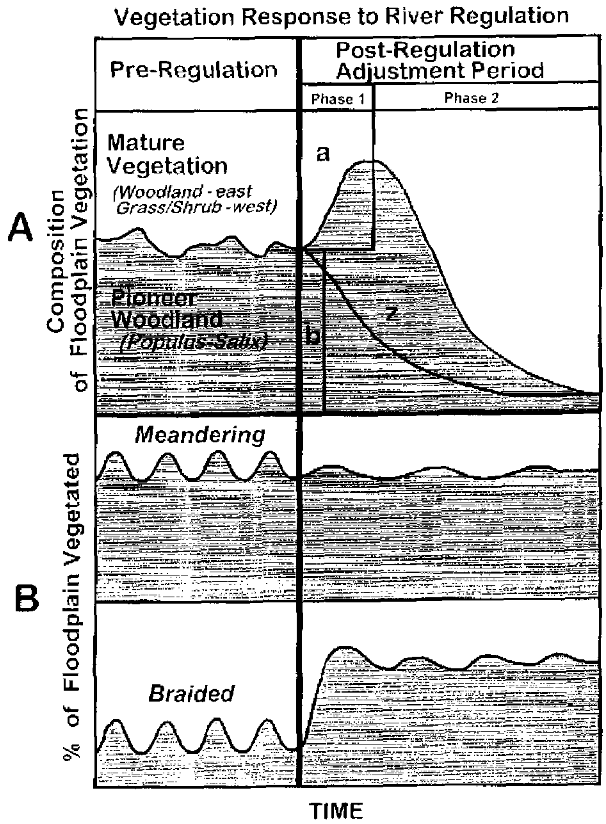

Figure 6. Response of riparian vegetation to streamflow regulation. Panel (A) depicts shifts in vegetation composition, and panel (B) depicts shifts in the proportion of the floodplain vegetated. The thick vertical bar marks the onset of regulation. Phase 1a pertains to adjustments on braided rivers such as the Platte, while phase 1b pertains to adjustments on meandering rivers such as the Missouri. Area z is a measure of the divergent response between braided and meandering river types.

The vegetation of braided rivers responds to regulation (peak flow reductions and dewatering) by expanding into the formerly active portions of the floodplain (Figure 6B). The magnitude of the expansion depends on the degree of regulation. Variation around mean area for both river types probably is lower after adjustment than before regulation. In contrast, the vegetated area on floodplains of meandering rivers shows little directional change during adjustment (Figure 6B).

The compositional response is more complex. In the pre-regulation period, woodland composition changes in response to high and low flow periods caused by the extremes of the weather cycle over shorter time periods and climate change over longer periods (Figure 6A). Friedman et al. (1996) have shown that channel width and vegetation composition and structure vary widely on unregulated rivers between extremes of the Great Plains climate. The notorious flooding of the pre-regulated Missouri River most assuredly caused avulsive channel meandering and rapid shifts in the balance between pioneer and later forest communities (Johnson et al. 1976). Similarly in the Platte River, the extent of vegetated area and the balance between pioneer and mature types (Figure 6) must have varied under presettlement flow conditions (Johnson 1994).

The response of vegetation to flow alteration by dams and diversions differs for braided and meandering rivers (Figure 6A). Braided rivers show large proportional increases in pioneer woodland (phase 1a) over a several decade period. Meandering rivers respond oppositely (phase 1b) because *Populus* fails to reproduce and establish without the formation of point bars.

Populus declines during phase 2 for both types of rivers but begins earlier for meandering rivers because phase 1 is shorter and no recruitment pulse occurs. Mature woodland as a proportion of total vegetation begins to increase during phase 2 for both rivers. When adjustment is complete, the low proportion of pioneer to mature vegetation contrasts with pre-development conditions for both types of rivers. However, total vegetated area is much greater in the post-regulation period for braided rivers.

The composition of mature vegetation differs along an aridity gradient from east to west in the Great Plains. While woodland comprised of later successional species dominates in the east, a grass/shrub community is expected to replace pioneer woodland species in the west (Figure 6A).

These models suggest that the geomorphic adjustment to regulation is relatively rapid (decades) and the subsequent adjustment of vegetation through succession relatively slow (century or more). Several other geomorphic factors may lengthen the time of adjustment. Changes in sediment supply from reservoir entrapment may be much slower to equilibrate (Petts 1987), particularly immediately below reservoirs and on rivers with cohesive banks (Williams and Wolman 1984). Clearly, coarseness of bed materials greatly influences the magnitude of the response and rate of adjustment to regulation (Church 1995).

For river reaches below dams experiencing slow channel incision due to an undersupply of sediment, the general model presented here may not apply. In such cases, morphological adjustment may be slower and the long-term consequences for vegetation unknown. Very little research has been conducted at the appropriate time scale to identify the singular effect of altered sediment supply on long-term vegetation dynamics along rivers.

Additionally, the general model proposed here assumes a single period of dam or diversion construction (either a single large structure upstream or multiple structures built over a short period). This is the case for the Missouri River example used but less so for the Platte River. For example, the data for the upper Platte River suggest an initially slower period of narrowing and woodland expansion related to diffuse upstream development prior to the late 1930s and a later period of accelerated change when larger dams and diversions were built closer upstream. Thus, some Great Plains rivers may have experienced more than one period in which flow and sediment were significantly altered. More complex, staged responses and incomplete adjustments may more accurately characterize protracted flow regulation than the single response case portrayed in Figure 6.

While the model is preliminary, it does appear to capture the extreme ends of the adjustment spectrum. These adjustment patterns segregate geographically, from dammed meandering-type rivers in the northern Great Plains to the dammed and diverted braided rivers in the central and southern Great Plains (see Friedman et al. 1998 this issue). More studies of the transient responses, adjustment rates, and new vegetation structure and composition after adjustment are needed to evaluate and expand the model.

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