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Reservoir effects on downstream river channel migration

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Summary

Human occupation and development of alluvial river floodplains are adversely affected by river channel lateral migration, which may range as high as several hundred metres per year. Reservoirs that reduce the frequency and duration of high flows typically reduce lateral migration rates by factors of 3 to 6. The ecology of riverine corridors is dependent upon the processes of erosion and sedimentation, which lead to lateral migration. Multiple-objective use of floodplains adjacent to active rivers therefore requires tools for assessing the probability and magnitude of channel movements. Existing approaches for predicting river channel movement may be classified as empirical or mechanistic, and are inadequate for widespread application. The Missouri River downstream from Fort Peck Dam in Montana, a major alluvial river with flow highly perturbed by regulation, was selected for case study. Maps and aerial photographs were available before and after dam construction. This imagery was analysed by digitizing channel centrelines at successive coverages under pre-dam and post-dam conditions, and mean migration rates were computed by bend and by reach. The mean rate of channel centreline migration fell from 6.6 m yr^{-1} to 1.8 m yr^{-1} after impoundment. Bend-mean channel activity rates were only weakly correlated with variables describing channel form and geometry. Results indicate that flow regulation for flood control and hydropower production typical of the study reach had profound effects on river corridor dynamism, with implications for habitat type distribution and ecosystem integrity.

Keywords: fluvial system, response, streambank erosion, riparian ecosystems, succession, meanders

Introduction

Alluvial rivers erode and deposit sediment along their banks, leading to migration of the channel across the floodplain. Rapid avulsions such as meander neck cutoffs also occur along more active systems. Rates of lateral migration vary widely in time and space, and observed values range from 0 to approximately 800 m yr^{-1} (Hooke 1980). Successional processes in floodplain forests depend upon periodic disturbance by riverine erosion and deposition, and the relatively high ecological diversity typical of riparian zones, particularly those in semi-arid landscapes, is maintained through habitat modification and construction (Johnson *et al.* 1976; Johnson 1992; Marston *et al.* 1995). Flood duration and timing, which drive erosion and deposition, are also important physical factors controlling riparian plant communities (Scott *et al.* 1997; Toner & Keddy 1997; Auble & Scott 1998). Response of riparian forests to regulation may occur over timescales of centuries (Church 1995; Johnson 1998). Animal populations are also affected by reduced channel migration rates; certain species of birds, for example, require large exposed bars that may disappear or become covered with vegetation following flow regulation (Pierce 1986 in Ligon *et al.* 1995). Channel avulsions are also responsible for creating abandoned channels, backwaters, and oxbow lakes that are key aquatic habitats within riverine ecosystems. River stabilization, either by structures or by elimination of high flows can result in the loss of these low-velocity habitats within a few decades as existing habitats are filled by sedimentation and no new ones are formed by migration or avulsion (Shields & Milhous 1992; Gore & Shields 1995; Shields *et al.* 1995).

Channel migration is often detrimental to various types of floodplain land-use by humans, and direct and indirect control methods are in great demand. Habitats associated with large temperate-zone rivers have been transformed by the cumulative effects of dams, bank stabilization and river control structures (Bravard *et al.* 1986, 1997; Ligon *et al.* 1995; Shields *et al.* 1995). Reliable methods for the prediction of alluvial channel migration would be useful in developing greater understanding of fluvial ecosystems and in planning for river corridor use to meet multiple objectives (e.g. economic development and ecosystem sustainability). Available methods for predicting bank line migration may be classified as involving empirical or mechanistic approaches.

Empirical approaches

River migration rate (e.g. area of floodplain reworked per channel length per year) has been empirically related to combinations of variables describing channel geometry (e.g. channel width, meander length, meander wavelength, amplitude, radius of curvature, arc angle and sinuosity) and discharges of various frequencies (Brice 1982; MacDonald *et al.* 1991; Garcia *et al.* 1994). Many investigators have noted relationships between bend migration rate and the mean

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bend radius of curvature, R_c (Hickin & Nanson 1975; Nanson & Hickin 1983; Hooke 1987; Biedenharn *et al.* 1989: Fischer 1994). Data from different reaches are typically normalized by dividing R_c by the mean channel width, W. These data sets show a nonlinear relationship with most rapid bend migration for values of R_c/W between 2 and 3, and less rapid rates for higher or lower values of R_c/W. For example, Nanson and Hickin (1983) fitted data from the Beatton River, British Columbia to the relations:

$$v = 0.6\ \mathrm{W/R_c}\ \text{for}\ \mathrm{R_c/W} \geq 3.125 \qquad (1)$$

and

$$v = 0.06\ \mathrm{R_c/W}\ \text{for}\ \mathrm{R_c/W} < 3.125 \qquad (2),$$

where v is the migration rate in m yr^{-1}. A physical explanation for the shape of this relationship has been proposed by Begin (1986). Using a simplistic conceptual model of flow in bends, Furbish (1988) argued that migration rate is a function of bend length as well as curvature, and that the Nanson and Hickin (1983) relation is a statistical artifact. Nevertheless, the relationship has been verified by several investigators using data from many rivers and provides a useful tool for practical problems (Hooke 1997).

Migration rates are further governed by the nature of boundary materials (Thorne 1992; Fischer 1994) and vegetation (Odgaard 1987; Beeson & Doyle 1995). Families of curves relating migration rate to R_c/W for various values of boundary resistance to erosion have been proposed by Hickin and Nanson (Hickin 1984).

Despite the volume of work done to develop empirical relations, the general nature of boundary materials and variables describing channel geometry fail to explain much of the variation in migration rate. Since channel migration is episodic, migration rates measured over shorter time periods (20–30 yr) exhibit greater scatter than those over 100–200 yr (Cherry *et al.* 1996), particularly for streams with banks that experience mass wasting (Beatty 1984). Furthermore, there appears to be no relationship between the rate of migration of a particular point on a river bank and corresponding values of local curvature divided by local width (Cherry *et al.* 1996). In contrast to the mean value for the bend, the migration rate at a particular point along a river reflects the behaviour of adjacent reaches, tributary influences, and overbank drainage (Fischer 1994), and perhaps the curvature and length of the portion of the bend immediately upstream from the point in question (Furbish 1988). The influence of adjacent reaches (for example, the influence of a rapidly growing bend just downstream) is the most difficult factor to account for in prediction (Hooke 1995).

Mechanistic approaches

In an effort to obtain process-based predictions, several workers have formulated mathematical models of the flow field in meander bends for predicting meander migration (Howard 1992; Mosselman 1995). Meander flow models necessarily involve simplifying assumptions, and most require input of a parameter describing the erodibility of the banks (Odgaard 1987; Hasegawa 1989). In the models the local bank migration rate v is given by the product of this parameter, termed the erosion coefficient (e), and the local excess velocity, which is the difference between the near bank velocity and the cross-section mean velocity:

$$\mathrm{v = e * (u_b - u)} \qquad (3)$$

where u_b is the near-bank depth averaged mean velocity, and u is the reach-averaged mean velocity. The erosion coefficient reflects many factors, but varies with grain size as does critical velocity or shear stress in a Hjulstrom or Shields-type relation (Hasegawa 1989). The mathematical meander migration models (e.g. Ikeda *et al.* 1981; Johannesson & Parker 1985) typically contain one-dimensional (streamwise) schemes with implicit representation of the cross-stream variations in flow or vertically-averaged two-dimensional representations of the flow field. Major shortcomings include the inability to predict outward bend growth (although simulation of downstream migration is good) (Garcia *et al.* 1994), reliance on a constant bank erosion coefficient even though bank erodibility may be highly variable in space, assumption of constant discharge and width (Cherry *et al.* 1996), and numerical instability for channels with high width-depth ratios. In addition, these models do not consider bank failure processes such as mass wasting or piping.

Reservoir effects on migration rates

Alluvial rivers tend to erode and lower their beds downstream of large reservoirs (e.g. Richards 1982; Williams & Wolman 1984; Ligon *et al.* 1995). Degradational trends are usually nonlinear functions of time since dam closure. The response of channel width (and bank erosion rates) to upstream reservoir closure is complex, with trends of widening, narrowing and no change reported for various rivers (Williams & Wolman 1984). Width adjustment, simplification of planform from braided or multi-thread to single thread, and propagation of riparian plants into previously unvegetated or lightly-vegetated areas, exhibit mutual interaction (Church 1995). Relatively little work has been done on the effect of dam closure on lateral migration rates. Studies of two rivers in the north central USA indicated migration rates were reduced by about 75% following dam closure (Bradley & Smith 1984; Johnson 1992). In contrast to these findings, the braided Hanjiang River in China exhibited a complex response to reservoir closure; the river experienced an initial reduction in bank erosion intensity of the same magnitude as for the USA rivers described above, from about 25 m yr^{-1} during 1955–60 to about 7.0 m yr^{-1} during the 17 yr period immediately after dam construction (Jiongxin 1997). However, as the river bed became coarser, bank erosion rates rebounded to levels (22–25 m yr^{-1}) typical of pre-dam conditions. Evidently, the coarser bed forced the banks to absorb

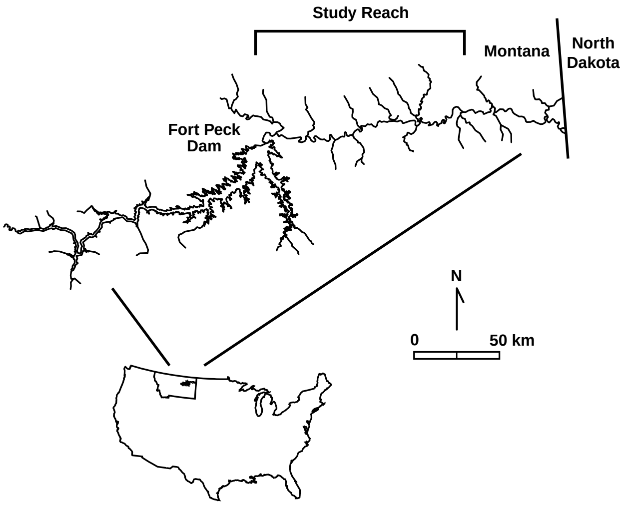


Figure 1 Location of study reach.

more of the energy of the flow; during the period of reduced bank erosion, the river degraded its bed, but after bed coarsening, degradation ceased and widening ensued (Jiongxin 1997). Based on a literature review, Friedman *et al.* (1998) suggested that the effects of dams on large rivers vary with the pre-existing planform: peak flow reduction by dams tends to cause braided rivers to narrow, while meandering rivers experience little change in width, but a reduction in migration rates.

We describe a case study involving the effect of a large dam on the migration rate of bends in an alluvial river. The objective of this study was to quantify reservoir effects on river migration rates and to explore the interaction of reservoir effects and migration processes in order to develop a foundation for sustainable management of the riverine corridor.

Study reach

The reach of the Missouri River in Montana between Fort Peck Dam and longitude 104°45′W was selected for study (Fig. 1) due to availability of historic map coverage. The climate is semi-arid with about 350 mm of annual precipitation, cold winters, and hot summers. Drainage area above the dam is 149 000 km^2, while the drainage area at the downstream end of the study reach is 232 000 km^2. Mean discharge is about 260 m^3 s^{-1}. Fort Peck Reservoir has a surface area and volume at maximum operation pool level of 970 km^2 and 23 km^3 respectively. The dam was constructed during 1933–37 and the reservoir reached minimum operation level in 1942. About 1.1 km^3 of sediment was retained by the reservoir between 1938 and 1987 (McGregor *et al.* 1996).

The river channel is entrenched in its floodplain, which is 3–5 km wide and bordered on the north by gently sloping uplands and on the south by steeper bluffs. Entrenchment preceded dam construction. The river is flanked by distinct terraces with the highest terrace about 3 m above the present high water level. In many reaches, river meanders are confined and contact the valley walls (McCombs-Knutson Associates, Inc. 1984; Wei 1997). Islands and bars are quite common in the channel, which has a top bank width of about 240–370 m. River slope is about 0.0002, and bed material is medium to fine sand with occasional deposits of coarse gravel, cobbles and dense clay. In 1993, the mean median bed sediment grain size varied from about 1.6 mm in the 110 km immediately downstream from the dam to about 0.25 mm in the reaches further downstream (Wei 1997).

Several straight channel segments occur, although the overall channel pattern corresponds well to the 'sinuous braided' river type (Brice 1984). Empirical relationships based upon bed slope, water discharge, and bed material size indicate that the study reach should have a meandering planform when it is in a state of dynamic equilibrium (Leopold & Wolman 1957; van den Berg 1995), while relationships proposed by Chang (1988) indicate that it is poised near the boundary between straight-braided and braided-point-bar forms. Apparently the channel is not free to fully develop meanders because of valley wall confinement, and the reach is in a state of dynamic equilibrium intermediate to the meandering and braided conditions. This condition has produced spatially intermittent braiding and several nearly straight sections with mean values of bend radius more than three times greater than those predicted by the formula of Langbein and Leopold (1966).

The main effect of Fort Peck Reservoir on study-reach channel geometry appears to have been degradation of the

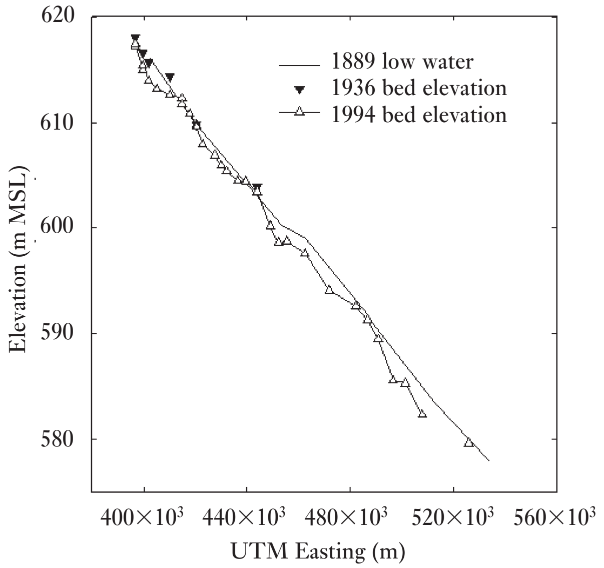


Figure 2 Elevation of the bed of the Missouri River downstream from Fort Peck Dam. The 1889 elevations are based on a low-water profile published by the US Army Corps of Engineers (1933). The dam was closed in 1937. The 1936 and 1994 mean bed elevations are from Wei (1997).

bed downstream of the dam (Williams & Wolman 1984; Pokrefke *et al.* 1998). The 1936 and 1994 cross-sectional mean bed elevations (Wei 1997) are plotted on the same axes with the 1889 low-water profile (US Army Corps of Engineers 1933) in Figure 2. Post-impoundment degradation has been most pronounced (up to 2.2 m) in the 10 km immediately below the dam, but an additional zone of severe degradation is located in the reaches 70–95 km and 120–140 km downstream from the dam. Analysis of repetitive surveys of six cross-sections located in the reach between the dam and 76 km downstream indicated that mean bed elevation decreased by as much as 1 m between 1936 and 1951 (US Army Corps of Engineers 1952), and by as much as 1.7 m by 1973 (Williams & Wolman 1984). Degradation was most rapid immediately after dam closure. Greatest degradation was observed at cross-sections 16 km and 23 km downstream from the dam. Channel widening at the six cross-sections varied from 0 to 37%. Geotechnical analysis of the effects of bed lowering on bank stability at 16 selected cross-sections located 10.5–294 km downstream from the dam indicated that six of the sites were less stable in 1994 than in 1937; however, destabilization was not greatest for sites with greatest bed degradation because of the influence of soil properties on bank stability (Simon *et al.* 1999*a*). Soil properties do not vary systematically with distance downstream from the dam.

The floodplain immediately adjacent to the river is intensely cultivated for irrigated sugar beet and grain production. Riparian landowners have contended that their operations are adversely impacted by bank erosion, which leads to an estimated mean annual loss of land of 0.12 ha per river km (US Army Corps of Engineers 1995). Planar failure due to toe scour and over-steepening by fluvial bank erosion is the most common mechanism of collapse (Pokrefke *et al.* 1998). Reported bank-erosion impacts include the loss of agricultural land, irrigation pumping stations and pipelines, damage to roads and bridges, and sedimentation in the downstream reservoir (Bernard *et al.* 1997). Some landowners contend that the riverine erosion and deposition processes are replacing high quality floodplain lands with lower elevation deposits of soils that are coarser and less fertile, while others simply contend that erosion of arable lands is not balanced by deposition (Rahn 1977).

Table 1 Maps and aerial photographic coverages used in this study.

Survey or photography dates	*Scale*	*Source*
1890–91	1:63 360	Missouri River Commission
1910–14	1:62 500	US Geological Survey
1971	1:24 000	US Geological Survey
1991	1:24 000	National Aerial Photography Program

Methods

Hydrology

Records of mean daily discharge and peak discharges for the gauge at Wolf Point, Montana, located about 103 km downstream from the dam, were obtained from the US Geological Survey for the period 1929–96. Due to the brevity of the pre-dam record (9 yr), data for the period 1929–37 collected at a gauge (Ft Benton, Montana) located 484 km upstream from the dam were used to generate a regression formula $r^2 = 0.73$, $p < 0.001$, $SE = 75\ m^3\ s^{-1}$) for pre-dam discharges

$$Q_{\text{Wolf Point}}(t) = 1.29\ Q_{\text{Fort Benton}}(t\text{-}5\ \text{days}) + 7.44 \tag{4}$$

Data from the upstream gauge were used with this formula to generate artificial records for the period 1890–1928. Graphical and statistical procedures (Hirsch *et al.* 1990; Richter *et al.* 1998) were used to compare the records prior to

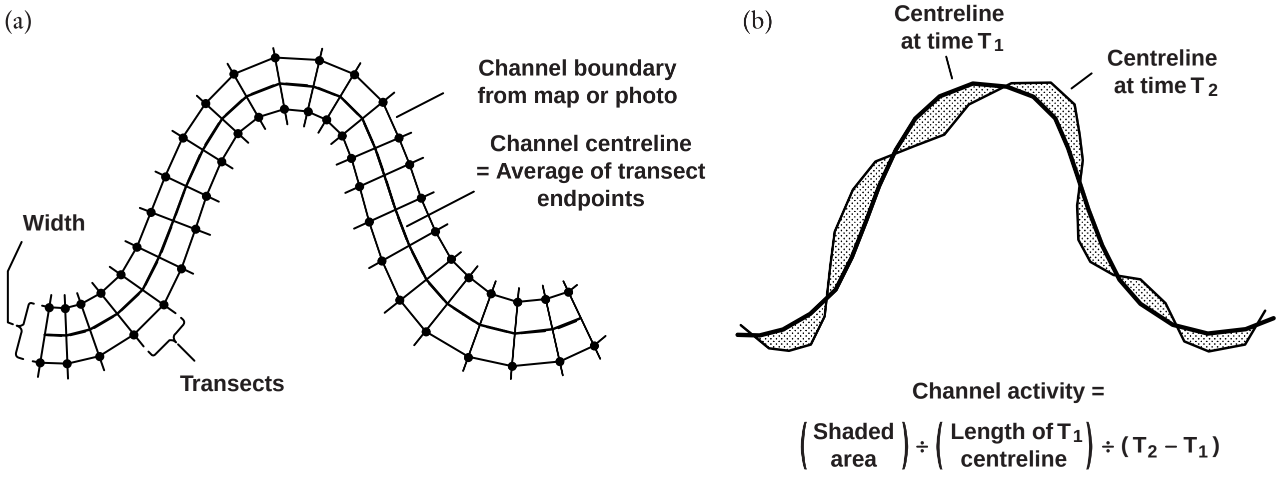


Figure 3 Methods for measuring channel geometry and activity (a) Determination of channel centreline location and channel width, (b) Determination of channel activity.

and following dam closure. Due to the non-normal frequency distribution of hydrologic data, medians and dispersion (the difference between the seventy-fifth and twenty-fifth percentiles) for extreme events (e.g. 7-day maximum flow) were examined to characterize alterations due to flow regulation.

Channel geometry

Government agencies and archives were contacted to locate maps of the study reach. In addition to the maps, black and white aerial photographs were obtained to provide modern coverage. Available maps and photos (Table 1) were organized to provide two pre-dam coverages (1890 and 1913–18) and two post-dam coverages (1968–71 and 1991). The water surface depicted on the maps or aerial photographs was assumed to be the channel. Transects running perpendicular to the channel were constructed at intervals of about 150 m, or roughly one-half of the stream width (Fig. 3*a*). Transects were drawn closer together in bends than in straight reaches to capture detail. Transect endpoints were defined as their points of intersection with the water's edge. Mid-channel bars were ignored, but bars attached to the bank line were treated as part of the bank. Transect endpoint coordinates were determined using a digitizer or a computer-aided drafting (CAD) system calibrated to a common coordinate system for each map or photo coverage. A railroad line paralleling the river was used to establish common registration between the 1890s and 1910s maps. Endpoint coordinates were transferred to a spreadsheet for analysis.

For each transect, the width was computed as the distance between endpoints, and the coordinates for the channel centreline were determined by averaging the endpoint coordinates. Channel centrelines were used for measuring meander characteristics. The 1890–91 and 1968–71 channel centrelines were plotted on paper, and radii of curvature and belt widths were measured manually. Radii of curvature were determined based on the radius of a circular arc fitted to the bend centreline between points of inflection. Bend lengths (distance measured along the channel) and meander half wavelengths (straight line distance between inflection points) were computed using centreline coordinates. Bend surface area was determined by numerical integration, and mean width was computed for each meander as the ratio of surface area to bend length.

Measurement of channel activity

Channel activity, defined here as the mean rate of lateral migration along a river reach in dimensions of length per unit time, has been measured in several ways by various investigators. Because of the limitations of available data, we determined channel activity by measuring the area enclosed by successive channel centrelines (Hooke 1987; MacDonald & Parker 1994), which was determined by computing the area of the series of polygons defined by the intertwined, digitized centrelines (Fig. 3*b*). Channel activity was then computed by dividing the sum of polygon areas for each bend by the length of the earlier of the two centrelines and the time between the two coverages. Survey or aerial photography dates for each map were used to date coverages rather than map publication dates. It is important to note that this method of measuring channel activity does not differentiate amongst various types of centreline migration. For example, gradual migration due to erosion of the outside of a bend, a major avulsion like a neck cutoff, and movement of the channel centreline due to attachment of a mid-channel bar to the bank, are all treated in a similar fashion.

Means of channel activity for the pre-dam and post-dam periods were computed and compared. Simple graphical and statistical approaches (correlation and regression) were used to examine relationships between channel activity and form variables (width, radius of curvature, meander half wavelength, bend length, and valley width) for pre-impoundment and post-impoundment data sets. Two analyses were performed.

- The first considered relationships between mean channel activity rates and form variables for each bend. The distance along the river channel from Fort Peck Dam to the bend apex and the amount of bed degradation observed over the period of record were used in addition to the form variables as independent variables. We hypothesized that the distance below the dam might serve as a surrogate for the strength of the effects of flow regulation on water and sediment discharge.
- The second analysis considered relationships between channel activity and the means of form characteristics computed for five subreaches bounded by major tributary confluences. Sub-reach channel activity was determined by dividing the sum of the area reworked within the sub-reach by the product of the length of the channel centreline and the time between the two coverages. Contributing drainage area, sinuosity, and meander-belt width were also used as independent variables. Centreline sinuosity was computed for each sub-reach by dividing the length of the channel centreline by the length of the valley centreline.

Due to the large number of unmeasured and site-specific variables, as well as the relatively low levels of precision we were able to generate from historical maps, we adopted a significance level $\alpha = 0.10$ for evaluating the strength of correlations between channel activity and form variables.

Results

Comparison of pre and post-dam river flows

Initial dam closure occurred in 1937, but the minimum operation level was not reached until 1942 (Wei 1997). Hydropower units were brought on-line in 1943 and 1961, and reservoir releases were elevated between about 1956 and 1965 to fill downstream reservoirs during a prolonged drought. The current operational regime therefore dates from the mid-1960s. In general, flow regulation by the dam

Table 2 Comparison of Missouri River mean daily discharges in m^3 s^{-1} before (1929–37) and after (1938–96) closure of Ft Peck Dam. Data also shown for period corresponding to interval used to measure post-dam channel activity (1971–91). Dispersion is defined here as the difference between the 75th and 25th percentiles.

	1929–37		*1938–96*		*1971–91*	
	Median of annual extrema	*Dispersion*	*Median of annual extrema*	*Dispersion*	*Median of annual extrema*	*Dispersion*
1-day minimum	51	10	107	75	150	60
7-day minimum	58	12	124	87	163	65
90-day minimum	88	18	167	84	215	64
1-day maximum	762	305	552	221	479	239
7-day maximum	572	286	492	197	431	172
90-day maximum	403	161	394	157	373	74
Rate of rise (m^3 s^{-1}/day)	19	12	13	7	12	5
Rate of fall (m^3 s^{-1}/day)	16	8	13	7	12	5
Julian date of minimum	346	18	284	114	276	72
Julian date of maximum	157	36	138	55	104	54

elevated low flows and depressed high flows. During the period just prior to dam closure (1929–36), mean discharge 113 river km below the dam was 200 m^3 s^{-1}, and the mean annual peak discharge was 765 m^3 s^{-1}. These values were 280 m^3 s^{-1} and 680 m^3 s^{-1}, respectively, after the dam was closed (1937–78) (Williams & Wolman 1984). The contrast between pre and post-dam discharges would be greater if not for the drought that dominated the short pre-dam period of record. During the period 1971–91, median values of the 1, 7, and 90-day minimum flows were all at least twice as great as for 1929–37 (Table 2).

High flow levels declined sharply following impoundment. Median values of 1 and 7-day maximum flows during 1971–91 were 63% and 75% of corresponding values for 1929–37. Between 1929 and 1964 there were 18 flood peaks greater than 710 m^3 s^{-1} recorded at the Wolf Point gauge, but only three peaks exceeded this level between 1971 and 1991.

Low flow variation became much sharper following impoundment, while high flow hydrographs became flatter. Variability of low flows (measured by 'dispersion' shown in Table 2, which is the difference between the 75th and 25th percentiles) increased by a factor of about six following impoundment due to hydropower operations. Dispersion of high flows declined slightly following dam closure, and the median rates of rise and fall were moderated (Table 2).

Similar analyses using artificial records for 1890–1929 in addition to the 1929–37 measurements show little change in median low flows following dam construction, but a halving of median high flows. For example, the median value of the 7-day maximum discharge was 1028 m^3 s^{-1} and 490 m^3 s^{-1} for the periods 1890–1937 and 1938–96, respectively. Effects of the dam on flow variability computed using artificial data were similar to those observed for the shorter period of record.

Reservoir effects on flow timing were particularly pronounced. Median discharges for low-flow months (August through February) were elevated by a factor of 2 to 3, while median discharges for high-flow months (April through June) were depressed by 10 to 30% (Fig. 4). During 1929–37, annual minimum flows occurred very late in the year (median Julian date for minimum = 346). In the period 1971–91, annual minima occurred about 75 days earlier. The median Julian date for annual maxima also shifted by a similar amount, from 157 before impoundment to 104 during 1971–91. Similar results were obtained for monthly medians and dates for extreme flows when the extended pre-dam data were used.

Channel geometry

Gross channel geometry varied little over the 100-year period of observation (Table 3). The channel depicted on the 1910–14 maps was about 20% wider than for the earlier and later coverages. The channel became slightly more sinuous

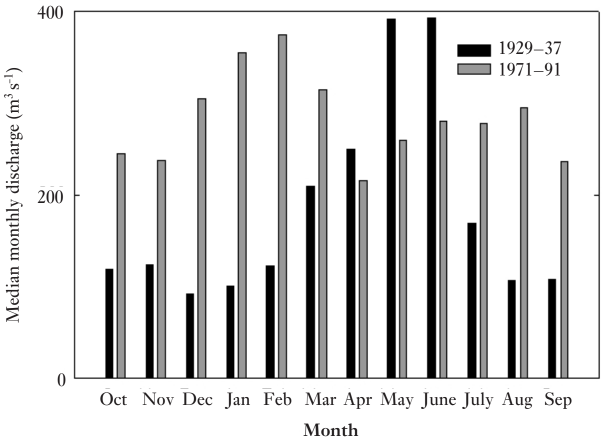


Figure 4 Median value of mean daily discharge in (m^3 s^{-1}) by month for Missouri River at Wolf Point, Montana. Time periods are selected intervals before and after closure of Fort Peck Dam.

Table 3 Properties of Missouri River channel downstream from Fort Peck Dam.

Variable	*1890–91*	*1910–14*	*1971*	*1991*
Mean width (m)	328	384	303	312
Total length of centreline (km)	203	201	205	204
Total area of water surface (ha)	6658	7718	6211	6365
Centreline sinuosity	1.47	1.46	1.49	1.48

after impoundment, with centreline length increasing about 2% in spite of a major neck cutoff, which shortened a 5 km bend to about 1 km sometime between 1913 and 1936 (Fig. 5).

Comparison of pre and post-dam channel activity

Channel activity rates were considerably higher prior to dam closure than afterwards (Fig. 6 and Table 4). About 3079 ha of floodplain were enclosed by the two pre-dam centrelines. This figure includes areas affected by five channel avulsions that may not have been eroded by the river channel. Only 722 ha were enclosed by centrelines derived from the two post-dam coverages. The mean rate of pre-dam channel activity was 6.6 m yr^{-1}, while the mean post-dam rate for the same reach between 1971 and 1991 was 1.8 m yr^{-1}.

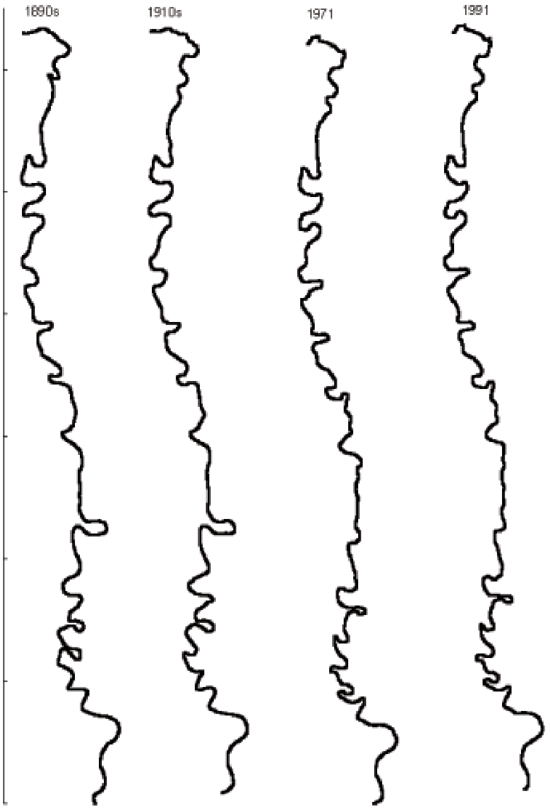


Figure 5 Successive centrelines of Missouri River downstream from Fort Peck Dam, Montana, before and after dam closure. North is to the right; flow is from top to bottom.

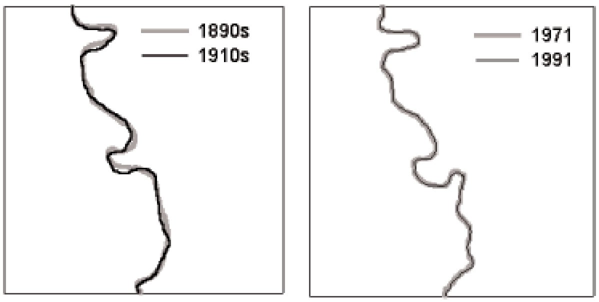


Figure 6 Superposed centrelines for typical reach of Missouri River downstream from Fort Peck Dam, Montana, for 20-year intervals before and after dam closure. North is to the right; flow is from top to bottom. Region shown is between fourth and fifth tick marks from bottom of vertical axis of Figure 5.

Bend activity and form variables

During both the pre-dam and post-dam periods, the highest values for bend-mean channel activity were associated with bends with rather low values of R_c/W. The critical range of R_c/W was between 2.7 and 5 (pre-dam) and between 3.1 and 4.3 (post-dam).

Bend-mean channel activity was slightly correlated with meander length ($r = -0.28$, $p = 0.0563$) prior to dam closure but with no other independent variables. Post-dam channel activity was positively correlated with width (Fig. 7). Eighteen per cent of the variation in bend-mean channel activity was explained by a multiple linear regression equation containing width and distance downstream from the dam. Channel activity was also examined in light of the magnitude of bed lowering following impoundment as depicted in Figure 2, but no relationships emerged. The study reach was divided into five subreaches bounded by major tributaries. Pre-dam reach-mean channel activity was inversely proportional to R_c ($r = -0.885$, $p = 0.046$), while post-dam reach-mean channel activity was positively correlated with reach means of R_c ($r = 0.822$, $p = 0.087$) and R_c/W ($r = 0.951$, $p = 0.013$). No other significant correlations were observed.

Discussion

Fort Peck Dam has reduced the magnitude and frequency of high flows and elevated low flows in the Missouri River downstream. Impacts on maximum flows are especially significant for rates of thalweg shifting (Jiongxin 1997), while effects on the rate of river rise and fall imply conditions prior to the dam favoured more bank failure (Simon & Curini 1998) and lateral migration (Chien 1961 in Williams & Wolman 1984). Fluvial response to the dam was primarily bed degradation and reduced lateral migration, with little change in mean channel width. This behaviour is consistent with the response of other meandering rivers in the region (Friedman *et al.* 1998). Since the earlier and later coverages depicted a narrower channel, the greater width for 1910–14

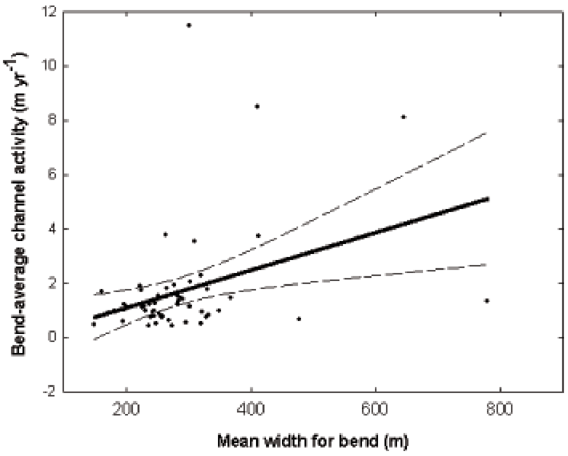


Figure 7 Post-dam channel activity as a function of width. Solid line is ordinary least-squares regression (activity = $-0.275 + 0.00691W$, $r = -0.358$, $p = 0.006$); dashed lines represent 95% confidence interval.

Table 4 Mean rates of channel activity, Missouri River downstream of Fort Peck Dam.

Variable	*Pre-dam*	*Post-dam*
Area worked (ha)	3079	722
Length of channel (km)	203	205
Mean channel centreline migration distance (m)	152	35
Mean rate of channel activity (m yr^{-1})	6.6	1.8
Maximum rate of channel activity for a single bend (m yr^{-1})	23	11

(Table 3) is probably due to differences in mapping conventions rather than morphologic differences.

Comparison with findings of others

We were unable to find measurements by others of pre-dam activity within our study reach. However, the post-dam rates we measured are in general agreement with the findings of others who used different data and measurement techniques. Measurements of the area of bank line eroded between successive aerial photographic coverages (US Army Corps of Engineers 1976; McCombs-Knutson Associates, Inc. 1984; Englehardt & Waren 1991; Pokrefke *et al.* 1998) may be converted to channel activity rates by dividing the sum of left and right bank areal erosion rates by reach length, yielding mean values of 2.7 m yr^{-1} for the period 1938–75 and 1.2 m yr^{-1} for 1975–83 (Table 5). The higher rate for 1938–75 relative to the later period is possibly related to water discharge. There was a mean of 13 days per year with discharge > 700 m^3 s^{-1} during 1938–75, but only 9 days per year during 1975–83. Analysis of repetitive channel cross-section surveys was used to compute volumes of material eroded from banks within the study reach by Pokrefke *et al.* (1998). If these volumes are converted to bank retreat rates by dividing by mean bank height, values result that are comparable to those determined herein for the post-dam period, namely 2.0 m yr^{-1} and 1.0 m yr^{-1} for the periods 1955–66 and 1955–78, respectively.

Study reach channel activity was 3.7 times greater prior to impoundment than at present, which is comparable to the findings of others studying the effects of similar flow regu-

Table 5 Rates of study-reach bank erosion determined by others using aerial photographs.

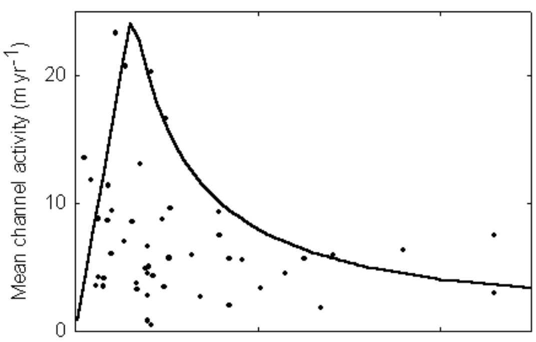
Time period	*Location (km downstream from dam)*	*Mean rate (m yr^{-1})*	*Source*
1938–75	52 to 74	1.9	US Army Corps of Engineers 1976
	80 to 120	1.9	Englehardt and Waren 1991
	132 to 148	3.2	
	192 to 226	3.1	
	266 to 300	3.6	
	mean for all reaches	2.7	
1975–83	0 to 304	1.2	McCombs-Knutson Associates, Inc. 1984
1933–83	0 to 304	1.8	Pokrefke *et al.* 1998

Table 6 Comparison of findings with other studies: effects of reservoir impoundment on channel migration rates.

River	*Location*	*Pre-dam migration rate (m yr^{-1})*	*Post-dam migration rate (m yr^{-1})*	*Pre/post*	*Reference*
Hanjiang	China	7.6	2.1[1]	3.6	Jiongxin (1997)
Milk	Downstream from Fresno Dam, Montana	1.7	0.5	3.4	Bradley and Smith (1984)
Missouri	Downstream from Garrison Dam, N. Dakota	5.6	1.3	4.3	Johnson (1992)
Missouri	Ft Peck to Brockton, Montana	6.6	1.8	3.7	This study (channel activity rather than bankline migration)

[1] Initial response; erosion later accelerated following bed armouring.

(a) Before impoundment



(b) After impoundment

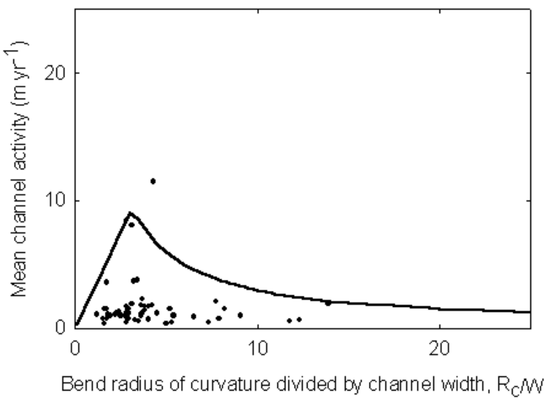


Figure 8 Bend-mean channel activity versus bend radius of curvature divided by bend-mean width (a) before and (b) after closure of Fort Peck Dam. Solid curves represent formula proposed by Nanson and Hickin (1983) multiplied by 40 in (a) and by 15 in (b).

lation on other meandering alluvial rivers (Table 6). This change is almost certainly due to the changes in peak flow levels and frequency following dam closure (Table 2). Jiongxin (1997) reported an initial reduction of about 70% of the migration rate of a braided Chinese river following flow regulation, and related thalweg shift rates to flow variability. The Milk River downstream from Fresno Dam in northern Montana, which is tributary to our study reach, experienced a reduction in migration rate from 1.7 m yr^{-1} to 0.46 m yr^{-1} following dam closure (Bradley & Smith 1984). The Milk River channel width decreased about 25%, and the bed was degraded about 1.5 m. The dam had little effect on mean discharge, but caused a 60% decrease in the magnitude of the two-year return flood and similar decreases in larger, less frequent events. Johnson (1992) examined the effects of Garrison Dam on migration rates of the Missouri River in central North Dakota. Before dam closure, the mean erosion rate for a 166 km reach was 93 ha yr^{-1}, but only 21 ha yr^{-1} afterwards. Much of the reach below Garrison Dam has experienced net channel widening since dam closure (Williams & Wolman 1984), and deposition rates of alluvial material to form islands and bars were reduced from 165 ha yr^{-1} before the dam to 1.3 ha yr^{-1} afterwards. Changes in meandering rates were associated with the effects of the dam on high flows. Mean annual flood and the maximum mean daily discharge for the 25 years following dam closure were only 30% and 19% as great, respectively, as events of similar frequency were during the 25 years preceding dam closure. Timing of peak flows was shifted from the period April to July before dam closure to winter (February and March) after closure. Additional analysis of the central North Dakota reach was performed by Patrick *et al.* (1982) who concurred that erosion and deposition rates declined after dam closure. Clearly, reservoirs that impose different types of flow regulation schemes (e.g. elevation of bankfull flow duration via interbasin transfer) would promote different fluvial responses.

The mechanisms linking high flow events and accelerations in channel activity were not examined by this study, but are likely to reflect higher levels of stream power and sediment transport capacity that are associated with higher flows. In addition, channel avulsions such as neck cutoffs, which are included in our channel activity data, usually occur when overbank flows adopt advantageous routes (Brice 1973). The elimination or reduction of overbank flows implies that channel changes must occur as a result of processes acting only on the banks, and not on the floodplains. Finally, mass wasting processes, which are governed more by soil moisture regime than by in-channel flows, are also accelerated when prolonged periods of high stage saturate banks, reducing soil strength and increasing unit weight (Simon & Curini 1998). Studies of unregulated streams in Illinois and Minnesota indicated that migration rates were proportional to the two-year discharge raised to the power of 0.52 (MacDonald *et al.* 1991; Garcia *et al.* 1994).

The values we computed for bend-mean channel activity are approximately associated with the bend R_c/W in a fashion similar to that described by Nanson and Hickin (1983), Hooke (1987) and others (Fig. 8) for bend-mean channel migration rates. The envelope of our observed channel activity data follows the curve proposed by Nanson and Hickin (1983) based on their study of Canadian rivers if the functions describing the curve (Equations 1 and 2 above) are multiplied by 40 and 15 for pre-dam and post-dam data sets, respectively.

Ecological significance

Channel migration typically promotes the establishment of certain tree species by providing new bare, moist soil surfaces (e.g. point bars) which are necessary for seedling establishment. Flooding supplies both seeds and moisture to these surfaces. Reduced levels of flooding and channel activity have been linked to declining populations of young pioneer tree species, principally cottonwood (*Populus* sp.) along rivers in the northern Great Plains of North America (Johnson *et al.* 1976; Bradley & Smith 1986; Johnson 1992; Friedman *et al.* 1998). Johnson (1992) estimated that pioneer forest covered 72% of the Missouri River floodplain in central North Dakota prior to European settlement, but only approximately 29% in 1979. Bradley and Smith (1986) found the mean density of cottonwood trees of ages 10–20 yr was six times lower downstream of Fresno Dam on the Milk River in northeastern Montana relative to an upstream reach in southern Alberta. Density of trees older than the dam and of trees $<$ 3 yr old was not reduced, indicating flow regulation and attendant channel stabilization adversely impacted survival but not germination of seedlings. Extrapolation of observed trends suggests eventual elimination of pioneer forest along many regulated rivers with attendant declines in habitat and faunal diversity (Johnson 1992). It should be noted that functional maintenance of riparian ecosystems is complex, and not likely to respond in a simple linear fashion to controlling physical variables. For example, a 50% change in channel activity may not produce a 50% increase in cottonwood recruitment. Complex responses occur when river planform shifts. For example, when braided rivers narrow, a temporary burst of establishment of woody species may be observed on the formerly active channel bed (Friedman *et al*. 1998).

Clearly, impacts of flow regulation on cottonwoods are not isolated, but merely indicators of broader, systemic effects. For example, a study of bald eagles (*Haliaeetus leucocephalus*) wintering along the Missouri River in South Dakota noted that 92.1% of floodplain tree perches used by the eagles were mature cottonwoods (Steenhof *et al*. 1980). The hydrologic and geomorphic changes that give rise to the impacts on riparian tree species also influence the aquatic community. Floodplain river ecosystems owe their great biodiversity to patterns of disturbance created by flooding and channel migration that give rise to a high level of spatio-temporal heterogeneity (Ward *et al*. 1999). Flow regulation of reaches of the Missouri downstream from our study, coupled with massive channel stabilization structures (stone revetments and training dykes to control erosion), have resulted in major reductions in aquatic habitat quantity (Morris *et al*. 1968), habitat diversity and quality (Hesse & Sheets 1993), commercial fish harvest (Hesse *et al*. 1989), and sport fishing (Groen & Schmulbach 1978), with attendant effects on fish species composition (Pflieger & Grace 1987). These effects are part of a global trend of habitat degradation and loss of biodiversity in major rivers (Hesse & Sheets 1993; Gore & Shields 1995; Ward *et al*. 1999).

Development of irrigated agriculture along the study reach has triggered interest in reducing channel activity even further in order to reduce risks associated with developing pumping sites and land loss. In view of the magnitude of the existing reduction and the potential ecological effects, it would seem desirable to reduce risk by adapting floodplain use based on maps of channel activity levels rather than insuring low levels of activity through river channel or river bank stabilization. Dunne (1988) produced a map of the Yakima River floodplain in Washington depicting three classes of channel activity hazard for a 25-yr planning horizon. This type of mapping requires some prediction of future channel activity, such as that based on empirical relationships derived from channel geometry. Current and historical (pre-dam) local (bend mean) channel activity for this reach of the Missouri River is only weakly related to channel form. Other workers have noted the difficulty of relating local channel migration, bank retreat, or channel activity rates to form variables (e.g. Hooke 1987; Cherry *et al*. 1996). Due to the large number of variables involved, empirical relationships between channel activity and one or two hydrologic or form variables are best suited to describing the behaviour of river channels averaged over large distances and over long periods of time (Cherry *et al*. 1996). Published relationships typically show mean rates of channel migration for long reaches of many rivers plotted against an independent variable (e.g. drainage area) that ranges over several orders of magnitude (e.g. Garcia *et al*. 1994). Drainage area for the study reach ranges from about 150 000 km^2 at the dam site to about 230 000 km^2, and spatial variation in water discharge is confined to a similarly narrow range. Accordingly, although channel activity increases slightly downstream in our data set and in data obtained by others (Table 5), variation in drainage area explains less than 3% of the variation in bend-mean channel activity in both the pre- and post-dam data.

Dunne's (1988) hazard map was based on a qualitative assessment of where channel avulsions were most likely to occur and projection of average recorded shifting rates. Avulsions were common along our study reach in the pre-dam period, and the largest values of bend-mean activity we recorded were associated with avulsions. However, the near elimination of overbank floods has greatly reduced the probability for neck cutoffs and other major avulsions. Neck cutoffs occur on bends where substantial elongation and neck constriction occur, with low values of bend radius of curvature. Future meander neck cutoffs will probably result from gradual narrowing of the meander neck by bank erosion rather than by creation of a chute during an overbank flood. However, rare events, such as floods and ice jams, can trigger neck cutoffs. The only recorded post-dam neck cutoff occurred in 1980 about 64 km downstream from our study reach. This event was triggered by an ice jam during a high flow event (Weismann 1993). There is only one meander bend in the study reach for which a neck cutoff appears imminent. Since avulsions are uncommon, and non-avulsive channel activity is hard to predict based on form variables, additional progress will require application of more mechanistic approaches for assessing the relative importance of soil moisture, vegetation, bank geometry, and bank soil properties on bank erosion and channel activity (e.g. Simon & Curini 1998; Simon *et al*. 1999*a*, *b*).

Conclusions

Closure of Ft Peck Dam has resulted in a four-fold reduction of the mean rate of channel activity of the Missouri River for 200 km downstream of the dam. This reduction is linked to the impact of reservoir operations on the frequency and duration of high flows. Channel activity for the period 1971–91 averaged 1.8 m yr^{-1} and values for a given bend ranged as high as 11 m yr^{-1}. The highest levels of activity have been in bends that experience channel avulsions. Existing technology for predicting lateral migration of river channels is not adequate to allow prediction of future channel activity. Empirical analyses of our data set indicated that post-dam channel activity varied directly with width and reach-mean R_c/W. Additional progress will be likely to require process-based modelling of geotechnical processes acting on high banks. Human use of floodplains depends on reducing risks associated with river erosion and sedimentation. However, in light of the likely adverse impacts on river corridor ecology, it seems unwise to achieve this goal by further reducing channel activity in the study reach. Strategies that preserve rather than limit natural riverine geomorphic processes are preferred (Ligon *et al.* 1995; Federal Interagency Stream Restoration Working Group 1998). To this end, floodplain land managers need better tools for assessing the probability and magnitude of river channel movements.

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