DTIC
Contract N68171-96-C-9014.

BANK STABILITY ANALYSIS FOR THE UPPER MISSOURI RIVER

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FINAL REPORT TO

EUROPEAN RESEARCH OFFICE
LONDON

FROM

UNIVERSITY OF NOTTINGHAM
UK

Under project number R&D ~~7791~~ 7836-EN-09

19970512 128

AUGUST 1996

ABSTRACT

Changes in the operation of Fort Peck and Garrison dams on the Upper Missouri River in Montana and North Dakota have been proposed as a means to enhance fisheries and wildlife interests, while continuing to fulfill essential flood-water storage and hydropower functions. Concern has been raised that the proposed changes in regulated flow regime may lead to accelerated rates of bank erosion. To investigate the possible impacts of the proposed regulated flow regime on fluvial bank erosion and bank stability with respect to mass failure, a field and modeling study was undertaken. Modeling studies were conducted using data at 18 study sites selected to represent the range of conditions encountered in the field.

Contemporary (September 1995) conditions of bank stability with respect to mass failure, identification of problem reaches, and identification of dominant erosion processes were characterized using stream reconnaissance. Based on field observations, 57% of banks in the Fort Peck dam reach and 41% of banks in the Garrison dam reach exhibit evidence of mass-wasting at the present time (September 1995).

The short-term (<5 years) impact on bank stability with respect to mass failure is analyzed by simulating changes in key bank hydrological parameters. Excess bank pore water pressures and hydrostatic confining pressures generated under the proposed flow regime are found to be indiscernible from those under the existing flow regime. Hence, short-term impacts on bank stability with respect to mass failure are negligible.

The long-term (up to 50 years) impacts on near-bank bed scour and fluvial bank erosion, and bank stability with respect to mass failure are analyzed by extrapolating historical trends of channel adjustment into the future under the existing flow regime. Estimates of the possible additional effects of the proposed flow regime (PFR) on these extrapolated trends are based on alterations to the sediment load of the river. Channel change is distributed uniformly along the study reaches, and estimates of resulting increases in cross-section area are negligible over a 50-year period. The dominant discharge values were found to be 200 m^3/s and 525 m^3/s, for the Fort Peck and Garrison dam reaches, respectively, for both existing (EFR) and proposed flow regimes. Since dominant discharge values are identical under both existing and proposed flow regimes, future rates of channel adjustment and trends of channel evolution are assumed equal for the two regimes.

Long-term (50 year) future rates of near-bank bed scour (0.0036 m/yr) and fluvial bank erosion (0.036 m/yr) averaged through the study reaches are small, though higher rates are predicted at a few specific sites due to localized conditions. These predictions indicate the channel is close to, or at, a condition of dynamic equilibrium.

Long-term changes in bank stability with respect to mass failure under the two flow regimes are predicted using the Darby-Thorne bank stability model. By the year 2045, the total length of unstable banklines in the study reaches is predicted to be approximately 55% to 65% for the existing and proposed flow regimes.

Keywords: bank erosion, channel change, dam, effective discharge, flow regulation, mass wasting, riverbank stability, stream reconnaissance

BACKGROUND AND INTRODUCTION

Changes in the operation of Fort Peck and Garrison Dams on the Upper Missouri River in Montana and North Dakota (Figure 1) have been proposed as a means to protect fisheries and wildlife interests, while continuing to fulfill essential flood-water storage and hydropower functions. The action agency responsible for river management and engineering (United States Army Corps of Engineers (COE)) is interested in predicting whether or not these operational changes might cause discernible impacts on bank erosion processes, bank stability with respect to mass failure, and rates of bankline migration. Annual hydrographs and flow duration curves for the existing and proposed operating regimes of Fort Peck and Garrison dams are shown in Figure 2. The proposed flow regime would have the effect of increasing discharge releases during spring and summer months, but decreasing discharge at other times (Figures 2a and 2b). Peak discharge will be increased from approximately 310 m^3/s to 400 m^3/s in the Fort Peck dam reach, but will be decreased from approximately 890 m^3/s to 840 m^3/s in the Garrison dam reach. In both reaches, existing baseflows will be reduced under the proposed operating schemes and the overall impact of proposed changes in dam operation will be to increase flow duration for relatively large magnitude flows and reduce flow duration for lower magnitude flows (Figures 2c and 2d).

There are three aspects of bank erosion mechanics that may be influenced by these changes in flow regulation:

(1) changes in the flow regime could alter the operational shear strength of the bank materials. Bank stability is increased by negative pore water pressures in the bank during low flow in the channel, and by confining hydrostatic pressure of water in the channel during high flows. Conversely, stability is decreased by excess positive pore water pressures in the bank during rapid drawdown in the channel following a high flow event. Such hydrological impacts

on stability with respect to mass failure would occur almost immediately after implementation of the proposed flow regime.

(2) changes in the rates of bank erosion can be expected if the magnitude and/or frequency of flows generating fluvial erosion are altered. Such changes would begin immediately following implementation of the proposed flow regime, and would continue until such time as a new condition of dynamic equilibrium was reached;

(3) changes in rates of bed-scour and sedimentation resulting from changes in the regulated regime might alter the profiles of banks along the study reaches, leading to changes in stability with respect to mass failure. Such changes would also begin immediately following implementation of the proposed flow regime, but their effects on bank stability with respect to mass failure would only become discernible some years later.

OBJECTIVES

The objectives of this study were to:

1) establish the channel form, bank stratigraphy, and present status of riverbank stability along the study reaches to locate critical sites experiencing accelerated bank erosion and mass-failure, and identify the erosion processes and failure mechanisms responsible for retreat;

2) estimate the short-term (1-5 years) impacts of proposed changes in the regulated flow regime on key bank hydrological parameters, and hence stability with respect to mass failure;

3) estimate the longer term (50 year) impacts of the regulated flow regimes on bank erosion and bed scour rates at 18 selected study sites;

4) estimate the impact of long-term (50 year) bank erosion and bed scour rates (estimated in (3), above) on bank geometry and bank stability with respect to mass failure at the 18 selected study sites.

STUDY AREA

The study area comprises two reaches of the Upper Missouri River (Figure 1). The first is a 190 river mile (304 km) reach of the Upper Missouri River extending downstream from Fort Peck dam, Montana (RM 1772) to the mouth of the Yellowstone River (RM 1582). The second is a 70 river mile (112 km) reach between Garrison dam (RM 1390) and Bismarck, North Dakota (RM 1320) (Figure 1). It should be noted that all river mile data presented here refer to the COE 1960 river mile classification (Missouri River Division, 1994). Channel and catchment characteristics are summarized in Table 1. In both reaches the bed material is predominantly sand, with coarser gravel located only in the upstream portions, close to the dams. Bank materials are composed of fine sand or silt (also observed by Williams and Wolman, 1984), and have little intrinsic cohesive strength (see Table 3). Table 3 also shows geotechnical data from other sandy/silty streambanks in other regions of the United States. In this study, data collection and analysis is for reaches with unprotected riverbanks. Riverbank protection is rather limited in the Fort Peck dam reach, but covers significant portions of banks along the Garrison dam reach.

METHODS AND STUDY APPROACH

The study was divided into three elements. First, a field reconnaissance of the study reach was undertaken to record contemporary channel conditions, locate unstable sites, identify dominant erosion processes and failure mechanisms (objective 1), and collect the data required to perform numerical bank stability analyses. Second, historical records of channel response to flow regulation in the study reaches were collected and interpreted to establish past response of the river to regulation and determine rates of bank erosion and bed scour. These historical data were then used as a basis for predicting future rates (objective 3). Finally, a numerical model was selected and applied to estimate present and future conditions of bank stability with respect to mass failure, under existing and proposed regulated river regimes (objectives 2 and 4).

Historical Data

Channel morphology data for the periods 1956 to 1978 (Fort Peck dam reach) and 1958 to 1985 (Garrison dam reach) have been collected by Omaha District COE and compiled in a report by the Missouri River Division (Missouri River Division, 1994). The MRD report includes bed elevation, bed width, and bed-material size data through time by river mile for both study reaches. These surveys were supplemented by additional mean-bed elevation and bed width data obtained from a report by Williams and Wolman (1984), extending the period of record from 1953 to 1985 in the Garrison dam reach, and increasing the number of observations to 5 and 8, for the Fort Peck and Garrison dam reaches, respectively. Flow and sediment transport data were supplied by Omaha District COE personnel and/or obtained from published United States Geological Survey (USGS) stream-gauging records.

Field Reconnaissance

A stream reconnaissance was made by boat in accordance with guidelines documented by Thorne (1993). Approximately 160 miles of bank (62% of the study reaches) were classified according to stratigraphy, profile, failure mechanism, and overall stability. Bank-failure mechanisms were classified as being of the planar, rotational, cantilever, piping/sapping, or pop-out type (Figure 3). Failure mechanisms were recorded on 1:24000 scale aerial photographs as the boat progressed downstream, and later used to estimate the locations and percentage lengths of stable and unstable banks, and the proportion of unstable bankline in each failure category. Notes were made regarding the geomorphic context of bank retreat at each location and, particularly, how failure categories related to position at channel bends. Photographs were taken at a total of 126 sites along the two study reaches. Examples of these photographs are shown in Plate 1.

Bank Stability Analysis

The riverbank stability analysis developed and tested by Darby and Thorne (1996) is suitable for use in this study. Simulations are based on bank profiles deformed by combinations of near-bank bed scour and direct fluvial entrainment (Figure 4). Upper bank failures can also be simulated, and the effects of pore water and hydrostatic confining pressures are included in the analysis. The analysis has also been shown to have better predictive ability than the alternative models of Lohnes and Handy (1968), Huang (1983), or Osman and Thorne (1988) (Darby and Thorne, 1996; see Table 2). The analysis is valid for cohesive, steep (bank angles greater than 50 degrees), eroding, non-layered riverbanks which fail along planar failure surfaces. Based on the results of field reconnaissance, this failure is the type most commonly observed along the study reaches (see Table 8 and Figure 9).

To apply the analysis, bank height, tension crack depth, relic tension crack depth and angle of the uneroded bank slope are required to describe the geometry of the bank profile (Figure 4). Cohesion, friction angle and unit-weight values are used to characterize geotechnical soil properties. Ground water and surface water elevations are used to simulate the effects of bank hydrology on stability. Input data parameters corresponding to bank conditions at the time of observation (September 1995) were obtained at 18 sites (13 in the Fort Peck dam reach and 5 in the Garrison dam reach), during field reconnaissance.

Sites were selected to cover a range of observed bank profiles, stratigraphies, and geomorphic locations, representative of the proportion of the bankline in each category of bank stability (Table 8). Cantilever, rotational, pop-out and piping/sapping type failures are not represented in the 18 study sites, since the numerical model is valid for planar failures only. This is justified because, on unstable banks, planar failures are the most common of the observed failure types (Table 8). Bank heights and tension crack depths were measured by standard surveying techniques and/or direct measurement with a survey rod. Average bank angles were obtained using a clinometer resting on a survey rod laid along the bank profile.

A hand held shear vane tester (SVT) was used to obtain *in situ* measurements of bank material shear strength on exposed bank faces. Ten measurements of bank material shear strength were obtained at 6 separate sites. Mean values of shear strength at the 6 sites were all close to 5.2 kN/m^2 (Table 3). Bank shear strength along the entire study reach was, therefore, characterized using this value.

Shear strength values can be resolved into cohesion and friction angle components using the Coulomb equation:

$$s = c + \sigma \tan \phi \tag{1}$$

where, s = soil shear strength (N/m^2), c = soil cohesion (N/m^2), σ = normal stress (N/m^2) and ϕ = friction angle (degrees). The value of normal stress is unknown when using the hand held shear vane testing device, but can be computed based on back calculations of observed failure block geometry (Figure 4), for which $\sigma = W_t \cos\beta = \gamma V \cos\beta$; where V = failure block volume per unit reach length (m^3/m) and γ = soil unit weight (kN/m^3). In addition to observations of failure block volume and failure plane angle, assumptions regarding the nature of the soils under "worst case" conditions were, therefore, required to estimate cohesion and friction angle components. "Worst case" conditions refer to the values of cohesion, friction angle and unit weight when the soil is saturated and most likely to fail (Thorne *et al.*, 1981).

Friction angle was assumed equal to 20 degrees for worst case conditions, because observations made during field reconnaissance indicate saturated bank materials come to rest at angles close to this value. This estimate is, therefore, considered reliable and accurate. Unit weight values were measured using laboratory analysis of samples taken from the field and are reliable and accurate. Worst case cohesion values were obtained by estimating values of the normal stress in equation (1) at the 6 bank material sampling sites by reconstructing failure block geometry based on measured bank profiles at those sites. Using the values $s = 5.2$ kN/m^2, $\gamma = 21.1$ kN/m^3, $V = 0.263$ m^3/m, $\beta = 50$ degrees, and $\phi = 20$ degrees (estimated using the assumption described above), a value of $c = 4.0$ kN/m^2 was obtained. Since the estimated worst case cohesion value was based on a back calculation using measured bank profile parameters (failure plane angle and failure volume), together with an estimated value of friction angle, worst case soil properties used in this study should be representative soils at the study sites. Also, soil property values derived and used in this study are comparable to values obtained by measurement on similar alluvial riverbanks (Table 3). Close correspondence between simulated and observed bank stability conditions at the study sites (see Results and Interpretation, below) for September 1995 conditions also supports the validity of this procedure. On this basis, it may be concluded that soil properties estimated using these procedures are reliable and sufficiently accurate to predict the impacts of river regulation on bank stability with respect to mass failure.

Estimation of Short-term Impact of Key Hydrological Parameters on Bank Stability

Worst case bank hydrology parameters, corresponding to the conditions most likely to trigger bank failure occur during the largest drawdown event of the annual hydrograph, because rapid drawdown results in relatively high phreatic-surface elevations coincident in time with relatively low water-surface elevations. This conditions generate maximum excess positive pore-water pressures and minimum hydrostatic-confining pressures simultaneously. Inspection of the hydrograph (Figures 2a and 2b) shows that, for the existing flow regime, maximum drawdown occurs between October and November at Fort Peck dam (approximate decrease in discharge from 325 m^3/s to 250 m^3/s). At Garrison dam, maximum drawdown also occurs between October and November (approximate decrease in discharge from 750 m^3/s to 520 m^3/s). Measured water-surface profiles along each study reach (Missouri River Division, 1994) were used to convert these discharge values to ground and water surface elevations (Table 6). The pre-drawdown water surface was assumed to represent the ground water elevation, with the post-drawdown surface representing the channel water surface. It was found that the pre-drawdown water surface elevation was equivalent to approximately 75% of the bank height, H (m), at most study sites. To simplify the calculations, the ground water elevation was therefore equated to this value at all sites (Table 6). Bank hydrology parameters for the proposed flow regime (Table 6) were estimated using the same procedure, but substituting discharge and water surface elevations appropriate for the proposed flow regime.

Bank-hydrology parameters for each flow regime were taken to be constant for bank stability analyses projected into the future, even though the estimates are based on measured water surface profile data which will actually change as channel morphology adjusts. The *relative* difference in ground and channel water surfaces caused by the change in discharge releases under the existing and proposed schemes is the dominant factor in influencing bank stability, rather than the *absolute* values of the water elevations themselves. While it is recognized that the magnitudes of estimated bank hydrology parameters will change, to attempt to account for these changes would introduce further uncertainty into the analysis and it is felt that the estimates in Table 6 based on existing conditions represent the relative values quite well.

Estimation of Effects of Long-term Changes in Bank Geometry on Bank Stability

Bank stability simulations were based on estimates of the values of future bank profile parameters for existing and proposed flow regimes, in conjunction with bank hydrological parameters corresponding to those two flow regimes (see above).

Existing flow regime

Channel-survey data for the periods 1956 to 1978 (Fort Peck dam reach), and 1953 to 1985 (Garrison dam reach) (Figures 5 and 6), were used to construct regression relationships between mean bed elevation versus time and bed width versus time at the 18 bank stability study sites (Table 4). Changes in mean bed-elevation versus time were assumed to be representative of changes in near-bank bed elevation through time, while changes in half bed-width through time were assumed to be representative of changes in flow erosion of the bank-toe through time. It is recognized that this may not be realistic for sites with highly non-uniform cross-sections, or at sites subject to local scour or flow impingement. However, this procedure appears reasonable, since aerial photographs and notes made during the field reconnaissance indicate that 14 of the 18 study sites are not subject to significant streamline curvature, flow impingement or other discernible local controls on bankline migration or near-bank bed scour.

Exponential and logarithmic regression curves were fitted to the data so obtained. Examples are shown in Figure 7. The regression relationship that most closely fitted the survey data (highest r^2 value) was selected for use in extrapolating future channel response to the regulated flow regime. Estimates of cumulative amounts of near-bank bed degradation (ΔZ) and bank-toe erosion ($\Delta W/2$) compared to estimated channel-bed conditions at the present time (1995) projected 1 (1996), 5 (2000), 10 (2005), 20 (2015) and 50 (2045) years into the future (Table 5) were obtained by extrapolation of the empirical regression curves listed in Table 4. It is stressed that the 1995 reference values of mean bed elevation and bed width are themselves extrapolated estimates, since the dates of the last surveys used to construct the regression curves are 1978 and 1985, for the Fort Peck and Garrison dam reaches, respectively.

At some sites, bed elevation and/or bed width were observed to be steady. In such cases, future bed elevations and bed widths were predicted to be constant and equal to the historical values. In all cases, estimates of lateral fluvial erosion increments were obtained by distributing predictions of overall change in channel-bed width equally between both banks. Extrapolation of fitted curves to predict future channel response has no physical basis, but empirical studies have indicated that, assuming boundary conditions do not change during the period of channel adjustment, fitted regression curves often describe the time evolution of morphological parameters quite well (e.g. Williams and Wolman, 1984; Lohnes, 1991; Simon and Hupp, 1992). Despite this, it should be recognized that the extrapolation approach to estimating future near-bank channel bed conditions is an approximate technique subject to limitations, and statistical error and uncertainty (Table 5). Hence, a range of ΔZ and $\Delta W/2$ values, based on the extrapolated values plus or minus the error estimates obtained at 95% confidence limits was used to support bank stability simulations.

Proposed flow regime

Future (1995 to 2045) bed elevation and bank-toe erosion trends for the proposed flow regime were estimated by comparing hydraulic and sedimentary regimes corresponding to existing and proposed flow regimes. Base data used to define the flow and sedimentary regimes of the study reaches are the flow duration curves for the existing and proposed Fort Peck and Garrison dam operating plans (Figures 2c and 2d), and suspended-sediment transport data from United States Geological Survey (USGS) gauging stations in the study reaches. In large rivers, a substantial fraction of the total load is wash load. However, it is the erosion, transport, and deposition of bed-material which is fundamental to the hydraulic shaping of the channel (Leopold, 1992; Thorne *et al.*, 1993). Suspended bed-material transport rates were estimated by excluding the silt fraction of measured load finer than 0.062 mm. The silt may be viewed as wash load passing through the system without playing a significant role in forming the channel. Data collected between 1958 and 1980 from gauges located at Culbertson (RM 1620) and Bismarck (RM 1320) in the Fort Peck dam and Garrison dam study reaches, respectively, were used to develop bed-material load rating curves:

$$Q_s = -120.1 + 62.8\ \mathrm{LOG}(Q) \qquad (r^2 = 0.84) \qquad (2)$$

$$Q_s = -738.7 + 302.2\ \mathrm{LOG}(Q) \qquad (r^2 = 0.79) \qquad (3)$$

where Q_s = suspended bed-material transport rate (kg/s) and Q = discharge (m^3/s).

Annual bed-material load data corresponding to each water discharge class for existing and proposed flow regimes were obtained by multiplying flow duration (converted to days) by bed-material transport rate (concentrations converted to tonnes per day). The results are shown in Figure 8. As expected, the impact of changing flow regime is to decrease the amount of bed-material transported by relatively low flows and increase the amount of bed-material transported by higher magnitude flows. In both reaches, the magnitude of the discharge class transporting the most bed-material is identical for the existing and proposed flow regimes (Figure 8 and Table 7).

A number of studies have indicated that the discharge transporting the most bed-material (termed the 'effective discharge') is the channel forming, or dominant discharge (Wolman and Miller, 1960; Hey, 1975; Andrews, 1980; Biedenharn and Thorne, 1994; Thorne *et al.* 1993). Many authors have also developed empirically-based hydraulic geometry equations (Leopold and Maddock, 1953; Simons and Alberston, 1960; Ackers and Charlton, 1970) relating stable-channel dimensions to dominant discharge (Q) using power equations of the form:

$$W = a\,Q^b \tag{4}$$

$$D = c\,Q^f \tag{5}$$

$$V = k\,Q^m \tag{6}$$

where W = stable channel width, D = stable channel depth and V = mean velocity, and a, c, k, b, f and m are empirical coefficients and exponents whose values are determined by regression. In this study, since the effective discharge values estimated for the existing and proposed flow regimes are unchanged, the impacts of the proposed flow regime on channel morphology are likely to be negligible.

The mean annual bed-material load in each study reach under both flow regimes is estimated by summing calculated values for each discharge class in Figure 8. Proposed changes in flow regime will increase the mean annual bed-material load for both study reaches (Figure 8 and Table 7). The morphological response to an increase in bed-material transport is usually erosion of the channel boundaries along the affected reaches. If perimeter erosion is distributed uniformly, and assuming that all of the increase in load is derived from perimeter erosion, reach-averaged cross-sectional area changes are obtained by dividing the volumetric load increase (obtained assuming a sediment density of 2650 kg/m^3) by reach length. The data in Table 7 indicate that predicted changes in cross-sectional area over a 50 year period are negligible, in agreement with the dominant discharge analysis. Future trends of bank erosion, bed scour and bank stability with respect to mass failure under existing and proposed flow regimes are therefore predicted to be indistinguishable.

RESULTS AND INTERPRETATION

Historical Context

Fort Peck Dam Study Reach

The primary morphological response of the channel to river regulation in the Fort Peck dam reach during the period 1956 to 1978 was bed degradation. This channel response downstream of a dam has been widely observed on many rivers, and is consistent with conclusions reached by Williams and Wolman (1984) and Borah and Bordoloi (1989), who attribute bed degradation to reduction in sediment supply following dam closure. Bed degradation during this period varied from about 0.6 m between Fort Peck dam and the Milk River confluence, to about 0.3 to 0.6 m downstream of Milk River (Figure 5a). With the exception of localized cases of narrowing or widening, little variation in active channel width through time had been observed up to the date of the latest available survey in 1978 (Figure 6a). The most recent survey (1978) indicates bed aggradation only in the furthest downstream portions of the study reach.

Garrison Dam Study Reach

The primary morphological response of the channel in the Garrison dam study reach during the period 1953 to 1985 was also bed degradation. This finding is also consistent with data reported by Williams and Wolman (1984) and Borah and Bordoloi (1989). Figure 5b shows that degradation has been greatest close to Garrison dam (approximately 2.4 m). Degradation decreases with distance downstream (approximately 0.91 m at RM 1340). Downstream of RM 1365, there appears to have been a recovery of bed elevation by 0.3 m to 0.6 m between the 1975 and 1985 surveys. Figure 6b indicates channel bed width reduction in the upstream reaches during the period 1975 to 1985, associated with bed incision observed in this period. Further downstream, the relationship between channel bed width and time is unclear.

Field Reconnaissance

Contemporary conditions of bankline stability are summarized in Figure 9 and Table 8. 57% of the banks reconnoitered in the Fort Peck dam reach display evidence of instability with respect to mass instability, compared to 41% in the Garrison dam reach. Planar failures are the most common mode of collapse, accounting for 45% and 59% of unstable banks in the Fort Peck and Garrison dam reaches, respectively. Popout (33% Fort Peck dam reach, 14% Garrison dam reach) and cantilever-type (19% Fort Peck dam reach, 27% Garrison dam reach) failures are also observed along shorter, but still significant, lengths of unstable bankline in both reaches.

Figure 9a shows a general tendency for the severity of bank instability observed during September 1995 to increase with distance downstream of Fort Peck dam. In contrast, bank instability decreases with distance downstream of Garrison dam (Figure 9b). Figure 9 shows that the only systematic change in failure mechanism versus distance downstream is a relative increase in the frequency of cantilever failures in the Fort Peck dam reach (Figure 9a). Planar failures are the most common mechanism of bank collapse in this reach (with the exception of sub-reaches between RM 1750-1730 and RM 1710-1690). Planar failures are dominant in three of five sampled sub-reaches of the Garrison dam reach, although classifications are based on a relatively small sample size in the other two sub-reaches.

Projected Bank Erosion and Bed Scour

Predictions of future fluvial bank erosion and near-bank bed scour for the existing flow regime (Table 5) were obtained by extrapolating the regression curves listed in Table 4. Statistical uncertainty in these extrapolations is represented by the 95% confidence interval.

Amounts of bed-scour after 50 years of channel adjustment range between -0.06 m (0.06 m of bed deposition) and 0.78 m for the 18 study sites. The mean rate of near-bank bed scour for the 18 sites averaged over the 50 year projection period is 0.0036 m/yr. Fluvial bank erosion for the 18 study sites ranges between 0 m and approximately 9 m over the 50 year projection period. The mean rate of fluvial bank erosion during this period is 0.036 m/yr. Mean rates of bed scour and fluvial bank erosion are low, indicating that the channel is at, or approaching, a condition of dynamic equilibrium. At some specific study sites (sites 8, 10, 11, 14, and 16), fluvial bank erosion rates are higher due to local conditions. There are also some study sites (sites 14 to 17), downstream of Garrison dam which are predicted to experience higher rates of bed scour. This may indicate continued local adjustment of the bed downstream of the dam.

Bank Stability Analysis

The Darby-Thorne bank stability analysis (Darby and Thorne, 1996) was applied at each of the 18 trial bank sites to produce quantitative estimates of bank stability for: (1) contemporary conditions; (2) conditions reflecting the short-term impact of the proposed flow regime on bank hydrological parameters, and; (3) conditions corresponding to projected future (1995 to 2045) channel changes under either flow regime.

Banks were classified into one of four categories (Plate 1):

(1) "Stable" banks have simulated factors of safety (*FS*), defined by the ratio of resisting to driving forces acting on the incipient failure block, greater than 1.3 (Plate 1a). Bankline retreat of geotechnically "stable" banks occurs only through fluvial erosion;

(2) "Marginal" banks have a simulated factor of safety between 1.1 and 1.3 (Plate 1b). Bankline retreat of "marginal" banks occurs through fluvial erosion, but they are vulnerable to geotechnical destabilization through relatively small increases in toe scour;

(3) "Upper Bank" banks have simulated factors of safety less than 1.1 with failure planes confined to the upper half of the bank. Bankline retreat occurs through combinations of fluvial erosion and mass instability (Plate 1c). Rates of bank retreat in this category are frequently more severe than those in categories (1) and (2), but are usually less severe than those of category (4);

(4) "Unstable" banks have simulated factors of safety less than 1.1 with failure planes intersecting the lower half of the bank profile (Plate 1d). Bankline retreat occurs through combinations of fluvial erosion and deep-seated mass instability. Rates of bank retreat in this category are commonly severe.

The factor of safety discriminating "unstable" and "marginal" banks is set here at 1.1, rather than the theoretical value of 1.0. This adjustment was made specifically to account for the tendency of the Darby-Thorne model to over-predict factor of safety (Darby and Thorne, 1996; Table 2).

Contemporary Conditions: Verification of Darby-Thorne stability analysis

Results of the Darby-Thorne analysis for current (1995) conditions are presented in Table 9. Bank profile, geotechnical, ground and surface water elevation input data, and corresponding simulated bank stability output data for each of the sections analyzed are listed. The analysis of contemporary bank stability is based on observed bank profile, geotechnical and bank hydrology parameters, measured during the September 1995 stream reconnaissance.

Six sites (3 in the Fort Peck and 3 in the Garrison dam study reaches) are predicted to be stable. Three sites, all located in the Fort Peck dam reach, are predicted to be marginal at present. Nine sites are predicted to be unstable, of which 6 are subject to upper-bank failures. In the Fort Peck dam reach, the 7 unstable sites are divided between 3 deep-seated and 4 upper-bank failures. The 2 unstable sites in the Garrison dam reach are predicted to be subject only to upper-bank failures at present.

54% and 40% of sites in the Fort Peck and Garrison dam reaches, respectively, are predicted to be subject to mass instability. These values are similar to the observed overall lengths of unstable bankline (57% and 41%) (Table 8). Discrepancies between predicted and observed failure categories occur at 5 (38%) of 13 sites (Table 9). Two of these involve inconsistencies between sites predicted to be marginal, but observed to be stable. At two of the remaining sites, the error is due to incorrect simulation of failure plane *location* on banks that are otherwise correctly predicted to be unstable. These discrepancies are within acceptable bounds for a reconnaissance study of this type.

Bank Stability Conditions: Short-term Impact of Proposed Flow Regime

Bank stability analyses were conducted to assess short-term (1-5 year) response to the proposed flow regime due to changes in bank hydrological parameters (Table 6). These simulations represent the effects of bank hydrological conditions in isolation because cumulative changes in bank profile parameters are too small at this time to affect the simulations.

One year into the simulation (1996), there are no significant differences between factors of safety for the flow regimes (Figure 10a). After five years (2000), differences in factor of safety become discernible (Figure 10b), but are still small. These differences are mostly insignificant because the predicted change is either insufficient to result in a shift in bank-stability classification, or because the predicted change occurs within a bank classification. Only at 2 (11%) of the 18 sites (sites 4 and 13, which are in the Fort Peck dam reach), do decreases in factor of safety result in a shift from "marginal" conditions under the existing flow regime to "unstable" conditions under the proposed flow regime (Table 10). On this basis, the short-term impact on bank stability with respect to mass failure of implementing the proposed flow regime is to modify the degree and type of instability rather than to increase the extent of instability along the study reaches.

Future Bank Stability Conditions

Bank stability analyses were repeated using input parameters for conditions projected 1 (1996), 5 (2000), 10 (2005), 20 (2015) and 50 (2045) years into the future. Since estimates of changes in perimeter erosion rates under the proposed flow regime are negligible (Table 7), results in this case are obtained from simulations conducted for the existing flow regime.

Bank profile data for future conditions were obtained by modifying bank-profile parameters measured during the September 1995 field reconnaissance (denoted by the subscript 'o' in the following equations) by the appropriate amounts of cumulative fluvial erosion and/or bed scour (Tables 5 and 8):

$$H = H_o + \Delta Z \tag{7}$$

$$H' = H'_o - (\Delta W/2) \tan i_o \tag{8}$$

Values of ΔZ and $\Delta W/2$ used in equations (7) and (8) were obtained from Table 5. Simulations were conducted using a range H and H' values, based on ranges of ΔZ and $\Delta W/2$ corresponding to 95% confidence intervals of the extrapolated regression curves. Simulations also accounted for the effects of bank hydrological conditions (Table 6).

Bank stability results at each successive date in the simulation are shown on Figure 10. The error bars on this figure reflect the uncertainty introduced into the factor of safety computations that results from using a range of values of ΔZ and $\Delta W/2$ in the bank simulation. After 50 years (2045), between 10 and 12 of the 18 study sites (56%-66%) are predicted to be subject to bank instability (Figure 10 and Table 10). These data compare with the observation that about 54% of contemporary (1995) banklines are subject to mass instability (Table 8). This indicates that the extent of bankline subject to mass bank failure will increase slightly over a 50-year period, under either the existing or proposed flow regimes.

CONCLUSION AND RECOMMENDATIONS

Conclusions

1. Stream reconnaissance suggests that at the present time (September 1995) 57% and 41% of the banks in the Fort Peck dam and Garrison dam study reaches, respectively, exhibit evidence of bank instability and mass-wasting. Field measurements of geotechnical characteristics indicate that bank material properties along the study reaches are relatively uniform. Bank materials are weakly cohesive (mean shear strength = 5.2 kN/m^2) sandy-silts. Planar failure due to toe scour and oversteepening by fluvial bank erosion is the most common mechanism of collapse in both study reaches;

2. The short-term (<5 years) impact on bank stability with respect to mass failure is analyzed by simulating changes in key bank hydrological parameters. Excess bank pore water pressures and hydrostatic confining pressures generated under the proposed flow regime are found to be indiscernible from those under the existing flow regime. Hence, short-term impacts on bank stability with respect to mass failure are predicted to be negligible.

3. In predicting long-term (up to 50 years) bed scour and fluvial bank erosion rates, it is essential to consider the historical context of channel adjustment trends along the study reaches. This is because existing trends of channel adjustment will drive ongoing channel adjustment under the existing flow regime. Any impacts of the proposed flow regime will produce divergence from these historical trends.

4. Future bed scour and fluvial bank erosion rates were predicted by extrapolating regression curves fitted to historical channel survey data. Long-term (50 year) future rates of bed scour (0.0036 m/yr) and fluvial bank erosion (0.036 m/yr) averaged through the study reaches are small, though higher bank erosion rates are predicted at some specific sites (sites 8, 10, and 11 in the Fort Peck dam reach, and sites 14 and 16 in the Garrison dam reach) due to localized conditions. Higher bed scour rates were also predicted at some specific sites (sites 14 to 17 in the Garrison dam reach). These predictions indicate the channel is close to, or at, a condition of dynamic equilibrium.

5. Analysis of the sediment regime of the study reaches under the existing and proposed flow regimes using measured data suggests that the annual suspended bed-material load will be increased by about 36% and 10% for the Fort Peck dam and Garrison dam study reaches, respectively. The dominant discharge is found to be about 200 m^3/s and 525 m^3/s in the Fort Peck dam and Garrison dam study reaches, respectively. These dominant discharge values are identical under both the existing and proposed flow regimes.

6. Estimates of the possible effects of the proposed flow regime on extrapolated trends of bed scour and fluvial bank erosion relative to the existing flow regime are based on alterations to the annual sediment load of the river and changes in the dominant discharge of the river. If perimeter erosion due to changes in sediment load is distributed uniformly along the study reaches, then estimates of resulting increases in adjustment rates are negligible over a 50-year period. Implementation of the proposed flow regime also has no impact on the dominant discharge of the study reaches. Future trends of bed scour and fluvial bank erosion are therefore predicted to be the same under either of the flow regimes.

7. Long-term changes in bank stability with respect to mass failure under the existing and proposed flow regimes are predicted using the Darby-Thorne bank stability model. Simulations are based on estimating the future values of bank hydrological parameters and bank geometry parameters under the two flow regimes. Bank geometry parameters 1, 5, 10, 20, and 50 years from September 1995 were obtained using the measured bank profiles deformed by cumulative amounts of bed scour and fluvial bank erosion for each flow regime (see conclusions 4, 5 and 6). By the year 2045, the total length of unstable bankline in the study reaches is predicted to be approximately 55% to 65%.

8. The Upper Missouri River has been regulated for the past 60 years. The channel is continuing to respond to the imposed flow and sediment regimes through erosion and sedimentation. Historical data indicate that rates of morphological adjustment through bed scour and fluvial bank erosion are decreasing with time. Bank instability with respect to mass failure will increase somewhat during the next 50-years, as a result of the cumulative effects of bed scour and toe erosion. On the evidence of this reconnaissance study, implementation of the proposed flow regime will have no discernible effect on any of these ongoing channel adjustments, compared to those predicted to continue under the existing flow regime.

Recommendations

On the basis of reconnaissance level morphological field and modeling studies performed in this project it has been concluded that about half of the banklines along the study reaches of the Upper Missouri River currently (1995) exhibit evidence of mass instability. Historical trends of channel adjustment indicate that the channel is approaching a condition of dynamic equilibrium, and on this basis it is unlikely that rates and extent of bankline retreat under the existing flow regime will increase significantly in the short-term. The modeling studies indicate a small increase in the extent of bankline instability with respect to mass failure, but this is within the range of uncertainty for a study of this type. However, we recommend ongoing monitoring of the extent and severity of bank instability with respect to mass failure to identify problems should they arise.

On balance, the results of morphological projections and bank stability modeling for the proposed flow regime suggest that the impacts on bed scour, fluvial bank erosion, and bank stability with respect to mass failure will be indiscernible from those of the existing flow regime. More detailed morphological investigations are, however, required to provide the scientific basis to evaluate this possibility and investigate the potential for localized adjustments which could adversely impact the riparian corridor. Morphological studies should take the form of a numerical water and sediment routing model coupled to further bank stability analyses.

ACKNOWLEDGMENTS

This study was funded by the US Army Engineer Waterways Experiment Station (WES) through the European Research Office under contract number 7836-EN-09. John Remus and John Garrison of Omaha District COE, and David Abraham (WES) assisted with fieldwork. John Remus provided flow data. Elaine Watts drafted the figures. Reviews of a draft report were provided by David Abraham, Ronald Copeland, Peter Downs, Tom Pokrefke, John Remus, David Sear and Andrew Simon. All these contributions are gratefully acknowledged.

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PLATE CAPTIONS

Plate 1. Examples of bank stability categories for sites along the Upper Missouri River (A) Unstable bank at RM 1719.5. Unstable banks have predicted factors of safety less than 1.1, with failure planes close to the toe. Note notching at base due to fluvial bank erosion. (B) Upper bank failure at RM 1761.5. Upper bank failures have predicted factors of safety less than 1.1 and failure planes are close to the floodplain. (C) Marginal bank at RM 1689. Marginal banks have factors of safety in the range ($1.1 \leq FS \leq 1.3$) and are not presently subject to mass instability, but may have been in the past, or may become so in the future. (D) Stable bank at RM 1597. Stable banks have $FS > 1.3$. The dense vegetation cover and relatively low bank angle indicate stability with respect to mass failure, but the tilted structure in the background indicates bank retreat has occurred at this site in the past.

Table 1 Summary of channel and catchment characteristics for Upper Missouri river between Fort Peck dam, Montana and Bismarck, North Dakota

Parameter	**Fort Peck dam reach**	**Garrison dam reach**
Date of dam closure	1937	1953
Drainage area above dam (km^2)	212,000	469,000
Baseflow discharge[a] (m^3/s)	210	520
Peak annual discharge[a] (m^3/s)	310	890
Average channel gradient	0.000174	0.000112
Bed material median diameter (mm)	0.25 - 10	0.25 - 12
Mean bank-material shear strength (kN/m^2)[b]	5.2	5.2

[a] Refers to existing dam operating regime

[b] Refers to conditions measured during field reconnaissance, not "worst case" conditions

Table 2 Accuracy of selected riverbank stability analyses (from Darby and Thorne, 1996). Factor of safety is defin as the ratio of resisting to driving forces acting on the incipient failure block. Observed factors of safety for critica banks are therefore equal to unity

Analysis	**Mean Predicted Factor of Safety**	**Mean Observed Factor of Safety**
Darby and Thorne (1996)	1.43	1.0
Osman and Thorne (1988)	1.82	1.0
Lohnes and Handy (1968)	1.83	1.0
Huang (1983)	3.26	1.0

Table 3 Comparison of values of estimated geotechnical characteristics of Upper Missouri bank materials and measured geotechnical characteristics of bank materials in the bluffline hills of northern Mississippi and of the Red River, Louisiana

Parameter	Upper Missouri	Bluffline Streams[a]	Red River[b]
Field Conditions			
Unit Weight (kN/m^3)	18.2	21.1	Not Stated
Shear Strength (kN/m^2)	5.2	Not Stated	Not Stated
Cohesion (kN/m^2)	Not known	4.3	Not Stated
Friction angle (degrees)	Not known	40	Not Stated
Worst Case Conditions			
Unit Weight (kN/m^3)	21.1	22.1	18.85
Cohesion (kN/m^2)	4.0	3.7	2.87
Friction angle (degrees)	20	20	27

[a] Data from Table 11 of Thorne *et al.* (1981)

[b] Data from Table 4.2 of Thorne (1992)

Table 4 Regression relations summarizing temporal trends of mean bed elevation and channel-bed width at bank stability analysis study sites. Regression relations for Fort Peck and Garrison dam reaches are based on data for periods 1955 to 1978 and 1953 to 1985, respectively

Site	RM	Mean Bed Elevation, Z (m)	Channel-Bed Width, W (m)
Fort Peck Dam Reach (t = years since 1955; n = number of data points used in regressions = 5)			
1	1688	$Z = 593.36$	$W = 374$
2	1682.4	$Z = 591.51 + 0.174\ \mathrm{LOG}(t)$ ($r^2 = 0.94$)	$W = 354.01 + 8.953\ \mathrm{LOG}(t)$ ($r^2 = 1.00$)
3	1674.5	$Z = 590.14\ 10^{-1.11043E\text{-}5t}$ ($r^2 = 0.75$)	$W = 499$
4	1669	$Z = 587.02$	$W = 244$
5	1647.5	$Z = 582.03$	$W = 320$
6	1642.5	$Z = 581.83$	$W = 408$
7	1638.2	$Z = 579.70$	$W = 352$
8	1631.3	$Z = 578.16 - 0.193\ \mathrm{LOG}(t)$ ($r^2 = 0.77$)	$W = 451.94 + 17.123\ \mathrm{LOG}(t)$ ($r^2 = 0.94$)
9	1619.9	$Z = 575.12 - 0.249\ \mathrm{LOG}(t)$ ($r^2 = 0.94$)	$W = 324.1$
10	1616.5	$Z = 574.22$	$W = 353.2 + 33.474\ \mathrm{LOG}(t)$ ($r^2 = 0.49$)
11	1612.8	$Z = 573.40$	$W = 352.85 + 35.205\ \mathrm{LOG}(t)$ ($r^2 = 0.49$)
12	1608.4	$Z = 572.39$	$W = 422.64$
13	1604	$Z = 571.53 - 0.048\ \mathrm{LOG}(t)$ ($r^2 = 0.94$)	$W = 399.27$
Garrison Dam Reach (t = years since 1953; n = number of data points used in regressions = 8)			
1	1386	$Z = 509.35 - 2.307\ \mathrm{LOG}(t)$ ($r^2 = 0.93$)	$W = 327.48 + 53.064\ \mathrm{LOG}(t)$ ($r^2 = 0.84$)
2	1379.8	$Z = 508.54 - 1.140\ \mathrm{LOG}(t)$ ($r^2 = 0.63$)	$W = 568$
3	1376.6	$Z = 508.20 - 1.412\ \mathrm{LOG}(t)$ ($r^2 = 0.95$)	$W = 903.74 + 36.896\ \mathrm{LOG}(t)$ ($r^2 = 0.79$)
4	1358.9	$Z = 504.78 - 1.361\ \mathrm{LOG}(t)$ ($r^2 = 0.84$)	$W = 506$
5	1346.4	$Z = 500.92 - 0.577\ \mathrm{LOG}(t)$ ($r^2 = 0.62$)	$W = 408$

Table 5 Cumulative values of future bed degradation and bank-toe erosion for existing and best-case proposed flow regimes compared to present (1995) estimate conditions, based on extrapolation of regression equations in Table 4. Note that 1995 values are extrapolated beyond last survey date of 1978 and 1985 for Fort Peck Garrison dam reaches, respectively. Error estimates are obtained from uncertainty of extrapolated values at 95% confidence intervals. Note: Negative values of ΔZ ind aggradation

Site	RM	Cumulative Bed Degradation, ΔZ (m)					Cumulative Bank-Toe Erosion, $\Delta W/2$ (m)				
		1996	2000	2005	2015	2045	1996	2000	2005	2015	2045
Fort Peck Dam Reach											
1	1688	0	0	0	0	0	0	0	0	0	0
2	1682.4	0 ± 0.02	-0.01 ± 0.06	-0.01 ± 0.11	-0.03 ± 0.19	-0.06 ± 0.38	0.05 ± 0.02	0.24 ± 0.06	0.45 ± 0.11	0.81 ± 0.19	1.61 ± 0.37
3	1674.5	0.01 ± 0.06	0.08 ± 0.08	0.15 ± 0.13	0.30 ± 0.22	0.75 ± 0.36	0	0	0	0	0
4	1669	0	0	0	0	0	0	0	0	0	0
5	1647.5	0	0	0	0	0	0	0	0	0	0
6	1642.5	0	0	0	0	0	0	0	0	0	0
7	1638.2	0	0	0	0	0	0	0	0	0	0
8	1631.3	0 ± 0.10	0.01 ± 0.47	0.03 ± 0.89	0.04 ± 1.60	0.07 ± 3.14	0.09 ± 0.02	0.45 ± 0.08	0.85 ± 0.15	1.54 ± 0.26	3.07 ± 0.52
9	1619.9	0 ± 0.01	0.01 ± 0.05	0.02 ± 0.10	0.03 ± 0.18	0.08 ± 0.35	0	0	0	0	0
10	1616.5	0	0	0	0	0	0.18 ± 0.26	0.88 ± 1.27	1.66 ± 2.39	3.01 ± 4.32	5.99 ± 8.49
11	1612.8	0	0	0	0	0	0.18 ± 0.06	0.90 ± 0.30	1.73 ± 0.57	3.15 ± 1.02	6.29 ± 2.01
12	1608.4	0	0	0	0	0	0	0	0	0	0
13	1604	0 ± 0.01	0 ± 0.03	0 ± 0.06	0.01 ± 0.10	0.01 ± 0.19	0	0	0	0	0
Garrison Dam Reach											
1 (14)	1386	0.02 ± 0.01	0.11 ± 0.04	0.21 ± 0.07	0.39 ± 0.12	0.78 ± 0.24	0.27 ± 0.01	1.30 ± 0.18	2.46 ± 0.34	4.49 ± 0.61	9.04 ± 1.21
2 (15)	1379.8	0.01 ± 0.01	0.06 ± 0.04	0.11 ± 0.07	0.19 ± 0.13	0.39 ± 0.26	0	0	0	0	0
3 (16)	1376.6	0.01 ± 0.06	0.07 ± 0.15	0.13 ± 0.26	0.24 ± 0.45	0.48 ± 0.86	0.19 ± 0.03	0.90 ± 0.15	1.71 ± 0.27	3.12 ± 0.50	6.28 ± 0.98
4 (17)	1358.9	0.01 ± 0.01	0.07 ± 0.04	0.12 ± 0.08	0.23 ± 0.16	0.46 ± 0.31	0	0	0	0	0
5 (18)	1346.4	0 ± 0.01	0.03 ± 0.04	0.05 ± 0.07	0.09 ± 0.12	0.19 ± 0.24	0	0	0	0	0

Table 6 Estimated worst case ground-water and surface-water elevations for existing and proposed flows

Study Reach	Existing Flow Regime		Proposed Flow Regime	
	Ground water elevation (m)	Surface water elevation (m)	Ground water elevation (m)	Surface water elevation (m)
Fort Peck Dam	0.75 H	0.75 H - 0.30	0.75 H	0.75 H - 0.60
Garrison Dam	0.75 H	0.75 H - 0.64	0.75 H	0.75 H - 0.76

Table 7 Estimated mean annual suspended bed-material load for existing and proposed flow regimes, dominant discharge, and projected reach-averaged increases in cross-sectional area

	Fort Peck dam Reach		**Garrison dam Reach**	
	Existing	**Proposed**	**Existing**	**Proposed**
Annual suspended bed-material load (tonnes)	5,800,000	7,900,000	13,300,000	14,700,000
Dominant discharge (m^3/s)	200	200	525	525
Increase in annual suspended bed-material load (tonnes)		2,100,000		1,400,000
Increase in annual suspended bed-material load (%)		36		10
Average annual increase in cross- (m^2/yr)		0.003		0.005
Increase in cross-section area over 50 years (m^2)		0.14		0.24

Table 8 Lengths of unstable and stable banklines (based on September 1995 field reconnaissance), and number of sites in each bank failure category

Category	**Fort Peck reach**	**Garrison dam reach**	**Number of study sites**
Study reach length (km)	288.0	112.0	Not applicable
Sampled bankline (km)	186.6	43.2	18
Stable bankline (km)	80.6	25.6	9
Unstable bankline (km)	106.6	17.6	9
Planar failure (km)	47.5 (45%)[a]	10.4 (59%)[a]	18
Popout failure (km)	35.6 (33%)[a]	2.4 (14%)[a]	0
Cantilever failure (km)	20.7 (19%)[a]	4.8 (27%)[a]	0
Rotational failure (km)	2.8 (3%)[a]	0.0 (0%)[a]	0

[a] Percentage based on length of unstable banks

Table 9 Darby-Thorne bank stability analysis for present (1995) conditions. Input data parameters based on values measured during September 1995 field reconnaissance. Symbols are defined previously

Site	River Mile	H (m)	H' (m)	α (degs)	K (m)	Kh (m)	γ (kN/m^3)	c (kPa)	φ (degs)	WSE (m)	GWSE (m	FS	H*	BW (m)	β (degs)	V (m^3/m)	Predicted Category	Observed Category
Fort Peck Dam Study Reach																		
1	1688	2.91	2.91	65	0	1.07	21.1	4	20	0.75H-0.3	0.75H	1.02	0.8	0.84	52.9	0.46	Secondary	Secondary
2	1682.4	3.66	3.66	78	0	0	21.1	4	20	0.75H-0.3	0.75H	0.59	0.05	2.39	49	4.35	Unstable	Unstable
3	1674.5	4.42	4.42	60	0	1.98	21.1	4	20	0.75H-0.3	0.75H	0.63	0.55	1.54	54.5	1.67	Secondary	Unstable
4	1669	3.35	3.35	50	0	0	21.1	4	20	0.75H-0.3	0.75H	1.13	0.05	1.87	35	2.98	Marginal	Marginal
5	1647.5	4.88	4.88	45	0	1.13	21.1	4	20	0.75H-0.3	0.75H	1.19	0.8	0.66	52.5	0.32	Marginal	Stable
6	1642.5	3.39	3.39	80	0	0	21.1	4	20	0.75H-0.3	0.75H	0.59	0.05	2.24	50	3.77	Unstable	Unstable
7	1638.2	5.8	5.8	60	0	2.61	21.1	4	20	0.75H-0.3	0.75H	0.54	0.55	2.02	54.6	2.87	Secondary	Unstable
8	1631.3	3.05	2.44	58	0	0.82	21.1	4	20	0.75H-0.3	0.75H	1.3	0.7	0.67	51.5	0.28	Stable	Marginal
9	1619.9	1.52	1.52	33	0	0.46	21.1	4	20	0.75H-0.3	0.75H	2.22	0.7	0.31	52.5	0.07	Stable	Stable
10	1616.5	1.83	1.83	40	0	0.3	21.1	4	20	0.75H-0.3	0.75H	3.51	0.85	0.19	52.5	0.03	Stable	Stable
11	1612.8	4.57	4.57	78	0	1.6	21.1	4	20	0.75H-0.3	0.75H	0.47	0.05	3.19	52.8	7.05	Unstable	Unstable
12	1608.4	7.92	7.92	40	0	2.38	21.1	4	20	0.75H-0.3	0.75H	0.56	0.7	1.93	54.4	2.59	Secondary	Secondary
13	1604	2.44	2.44	55	0	0.3	21.1	4	20	0.75H-0.3	0.75H	1.19	0.05	1.58	37.7	1.62	Marginal	Stable
Garrison Dam Study Reach																		
1	1386	5.49	5.49	45	0	0.91	21.1	4	20	0.75H-0.6	0.75H	1.36	0.85	0.56	52.5	0.23	Stable	No Photo
2	1379.8	5.49	5.49	38	0	1.37	21.1	4	20	0.75H-0.6	0.75H	1.09	0.8	0.75	52.5	0.41	Secondary	No Photo
3	1376.6	5.79	5.49	60	0	2.74	21.1	4	20	0.75H-0.6	0.75H	0.52	0.5	2.22	54.4	3.46	Secondary	No Photo
4	1358.9	2.44	2.44	50	0	0.61	21.1	4	20	0.75H-0.6	0.75H	1.73	0.75	0.41	52.5	0.13	Stable	No Photo
5	1346.4	3.78	3.78	50	0	0.46	21.1	4	20	0.75H-0.6	0.75H	2.28	0.85	0.44	47	0.1	Stable	No Photo

Table 10 Number of sites in each stability category simulated for future conditions.

Category	1 Year (1996)	5 Years (2000)	10 Years (2005)	20 Years (2015)	50 years (2045)
Unstable	3 (17%)	3 - 4 (17 - 22%)	4 - 7 (22 - 38%)	5 - 7 (28 - 39%)	5 - 7 (28- 38%)
Upper- Bank	6 (33%)	6 (33%)	5 (28%)	6 (33%)	5 (28%)
Marginal	4 (22%)	4 - 5 (22 - 28%)	3 - 4 (17 - 22%)	4 (22%)	3 - 4 (16- 22%)
Stable	5 (28%)	3 - 5 (17 - 28%)	3 - 5 (17 - 28%)	1 - 3 (6 - 17%)	2 - 5 (12- 28%)

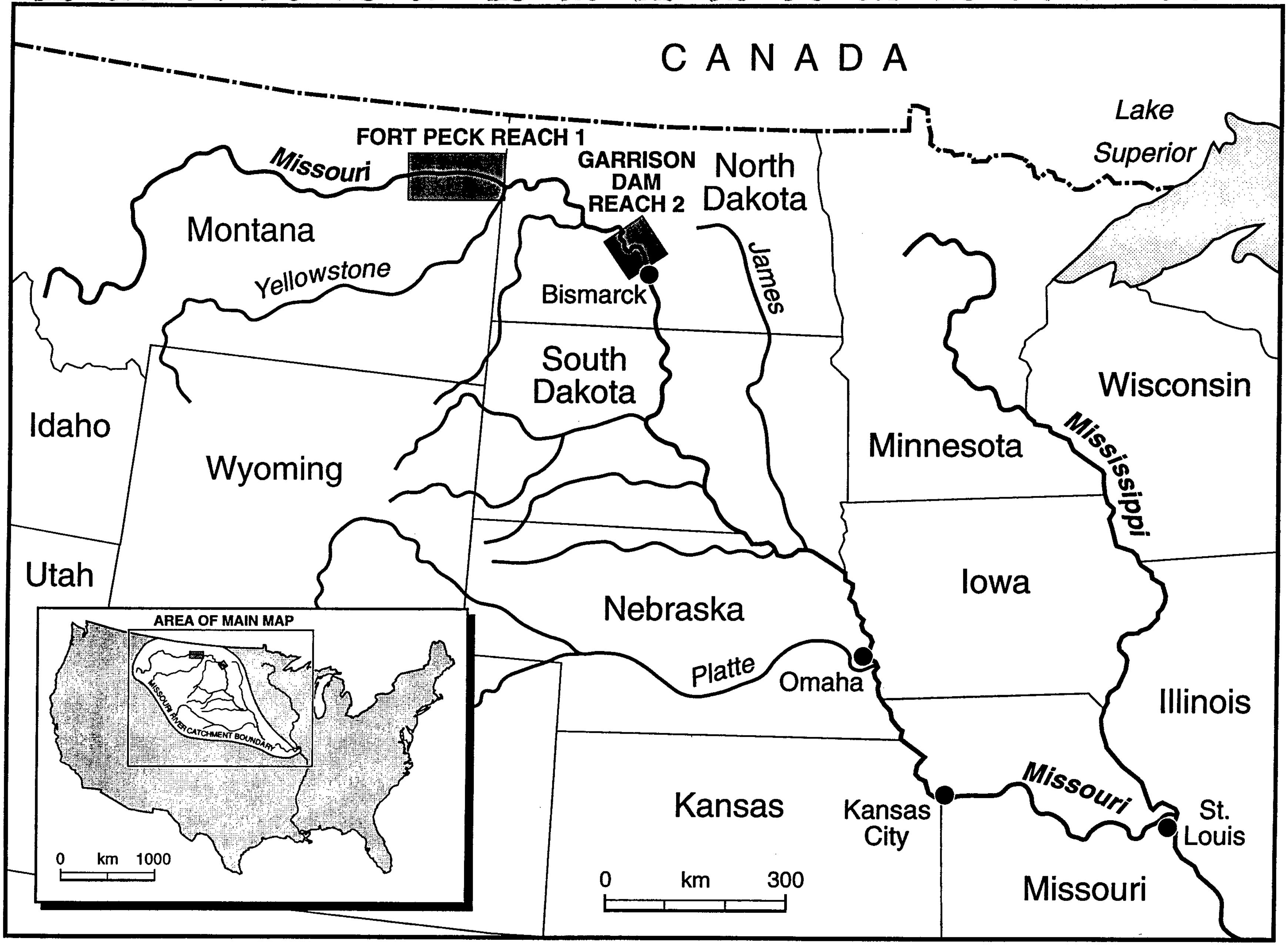

CANADA
FORT PECK REACH 1
GARRISON DAM REACH 2
Missouri
Montana
Yellowstone
North Dakota
James
Bismarck
South Dakota
Lake Superior
Wisconsin
Mississippi
Minnesota
Idaho
Wyoming
Utah
Iowa
Nebraska
Platte
Omaha
Illinois
Kansas
Kansas City
Missouri
St. Louis
Missouri
0 km 300
AREA OF MAIN MAP
MISSOURI RIVER CATCHMENT BOUNDARY
0 km 1000

FIGURE 1

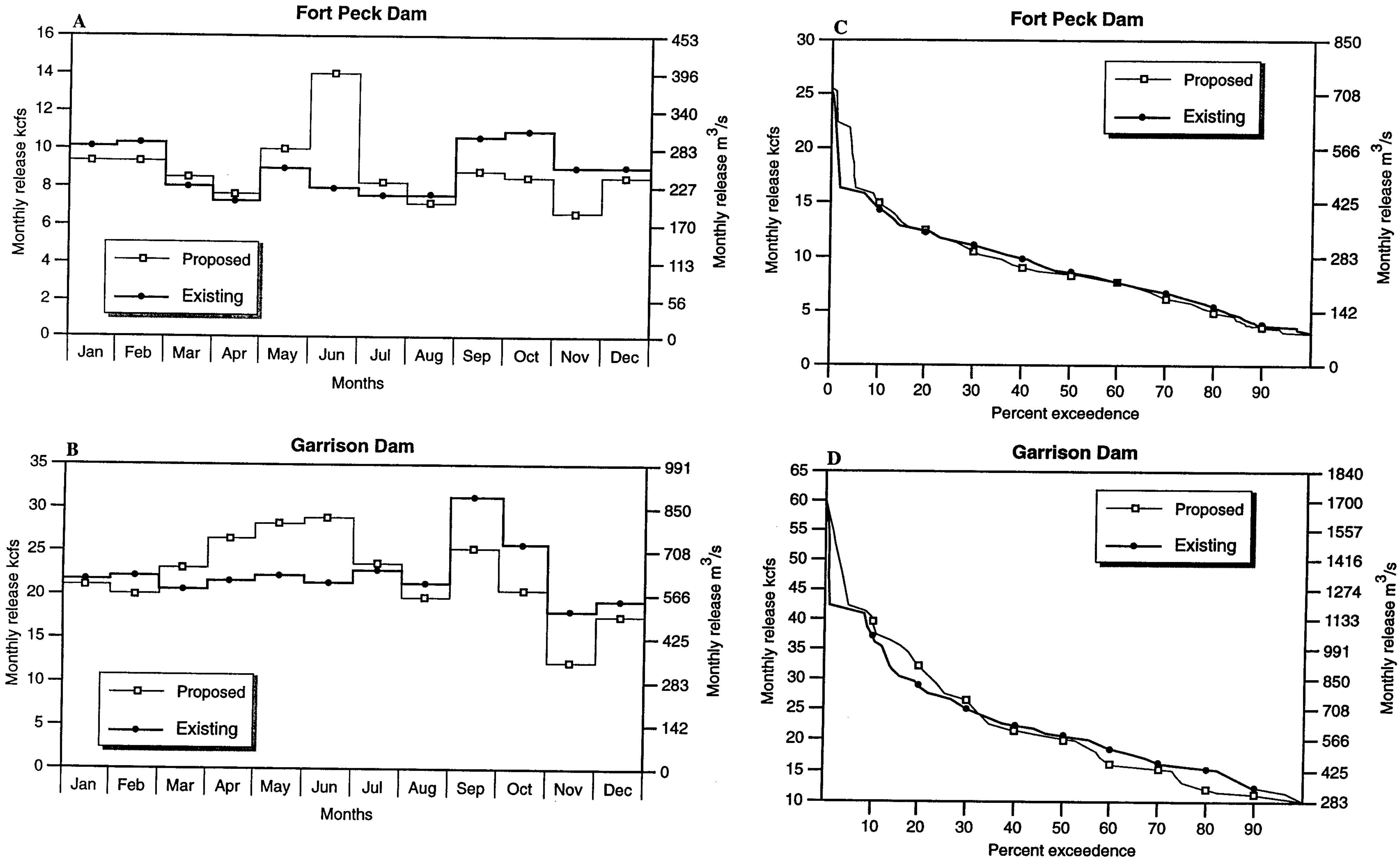
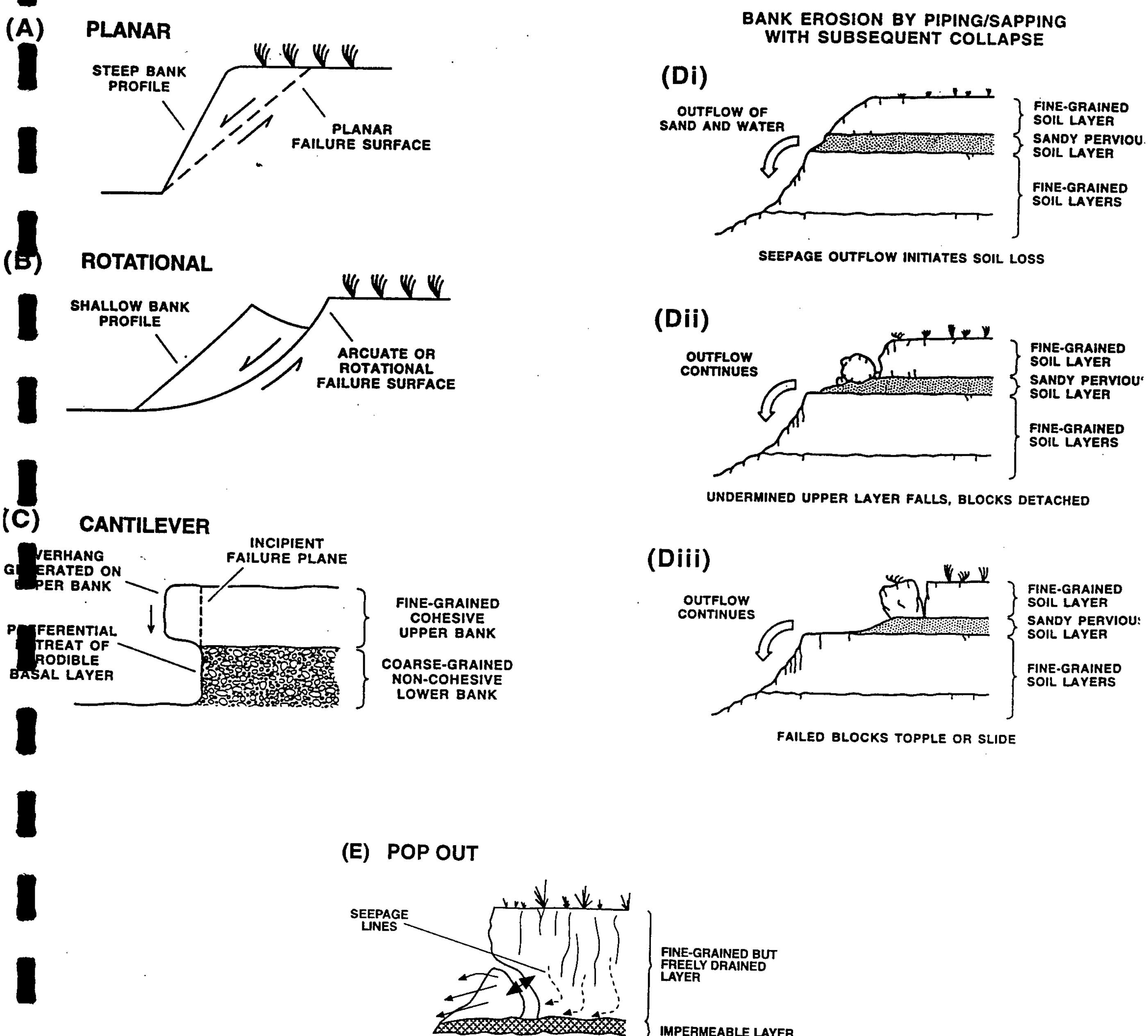

A
Fort Peck Dam
Monthly release kcfs
Monthly release m3/s
Proposed
Existing
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Months
C
Fort Peck Dam
Percent exceedence
B
Garrison Dam
D
Garrison Dam

FIGURE 2

FIGURE 3


(A) PLANAR
STEEP BANK PROFILE
PLANAR FAILURE SURFACE
ROTATIONAL
SHALLOW BANK PROFILE
ARCUATE OR ROTATIONAL FAILURE SURFACE
(C) CANTILEVER
VERHANG
ERATED ON
PER BANK
INCIPIENT FAILURE PLANE
FERENTIAL
TREAT OF
RODIBLE
SAL LAYER
FINE-GRAINED COHESIVE UPPER BANK
COARSE-GRAINED NON-COHESIVE LOWER BANK
BANK EROSION BY PIPING/SAPPING WITH SUBSEQUENT COLLAPSE
(Di)
OUTFLOW OF SAND AND WATER
FINE-GRAINED SOIL LAYER
SANDY PERVIOU SOIL LAYER
FINE-GRAINED SOIL LAYERS
SEEPAGE OUTFLOW INITIATES SOIL LOSS
(Dii)
OUTFLOW CONTINUES
FINE-GRAINED SOIL LAYER
SANDY PERVIOU SOIL LAYER
FINE-GRAINED SOIL LAYERS
UNDERMINED UPPER LAYER FALLS, BLOCKS DETACHED
(Diii)
OUTFLOW CONTINUES
FINE-GRAINED SOIL LAYER
SANDY PERVIOU SOIL LAYER
FINE-GRAINED SOIL LAYERS
FAILED BLOCKS TOPPLE OR SLIDE
(E) POP OUT
SEEPAGE LINES
FINE-GRAINED BUT FREELY DRAINED LAYER
IMPERMEABLE LAYER

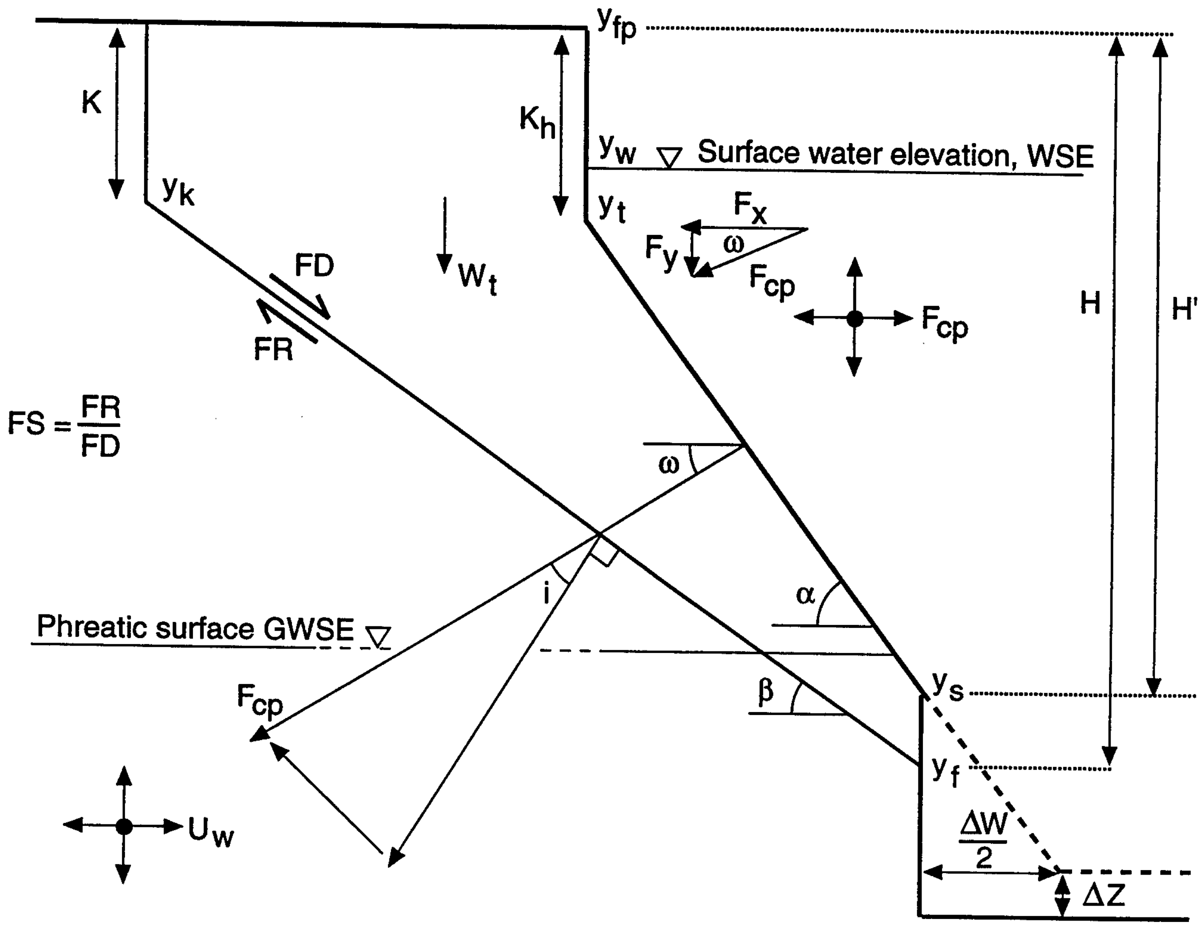

y_{fp}
K
K_h
y_w
Surface water elevation, WSE
y_k
y_t
F_x
F_y
ω
F_{cp}
FD
W_t
FR
F_{cp}
H
H'
FS = FR/FD
ω
α
i
Phreatic surface GWSE
β
y_s
F_{cp}
y_f
U_w
ΔW/2
ΔZ

FIGURE 4

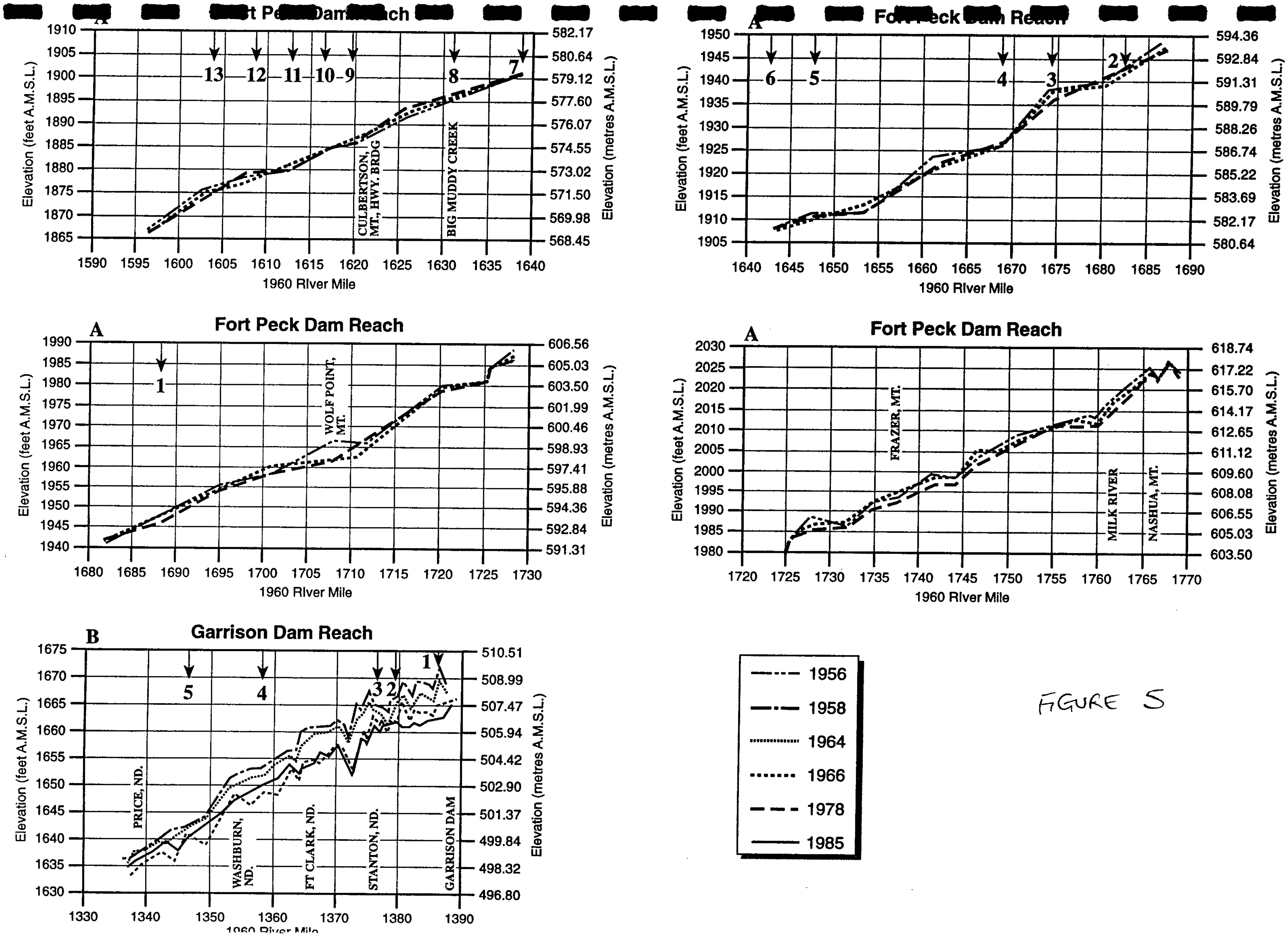
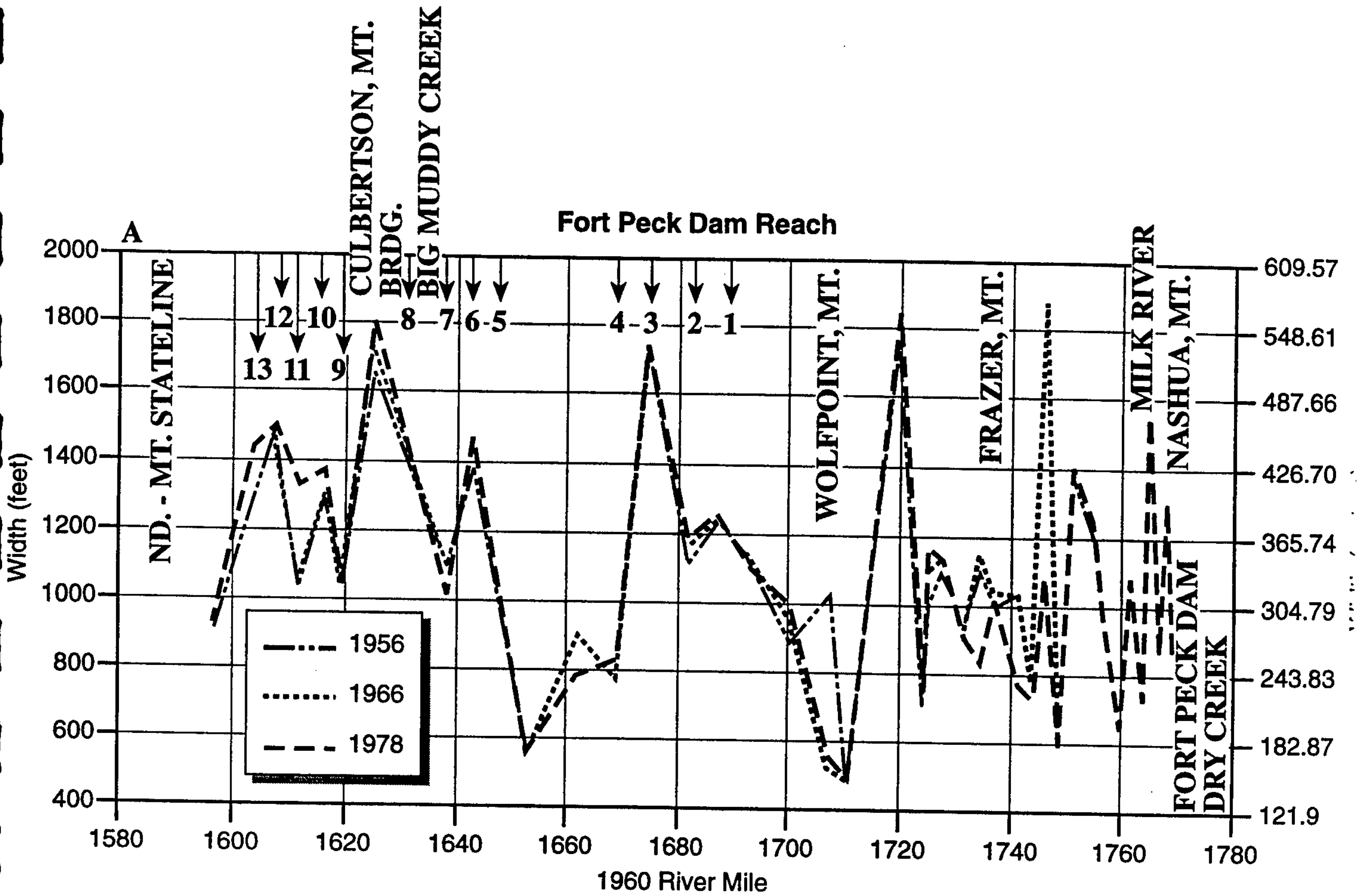

Fort Peck Dam Reach
Fort Peck Dam Reach
A
B
Garrison Dam Reach
Elevation (feet A.M.S.L.)
Elevation (metres A.M.S.L.)
1960 River Mile
CULBERTSON, MT., HWY. BRDG
BIG MUDDY CREEK
WOLF POINT, MT.
FRAZER, MT.
MILK RIVER
NASHUA, MT.
PRICE, ND.
WASHBURN, ND.
FT CLARK, ND.
STANTON, ND.
GARRISON DAM
1956
1958
1964
1966
1978
1985

FIGURE 5


A
Fort Peck Dam Reach
Width (feet)
1960 River Mile
1956
1966
1978
ND. - MT. STATELINE
CULBERTSON, MT. BRDG.
BIG MUDDY CREEK
WOLFPOINT, MT.
FRAZER, MT.
MILK RIVER
NASHUA, MT.
FORT PECK DAM
DRY CREEK
13 12 11 10 9 8 7 6 5 4 3 2 1
609.57
548.61
487.66
426.70
365.74
304.79
243.83
182.87
121.9

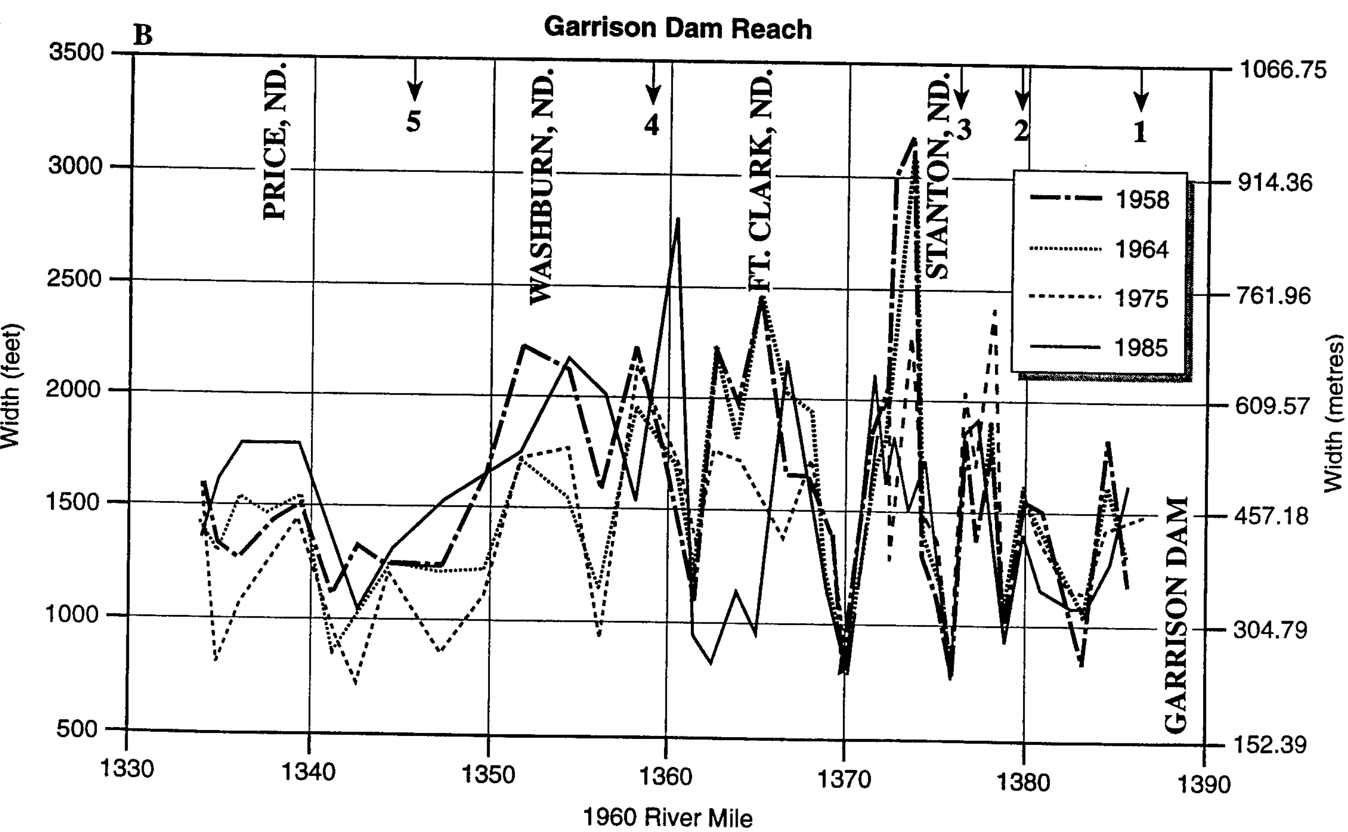
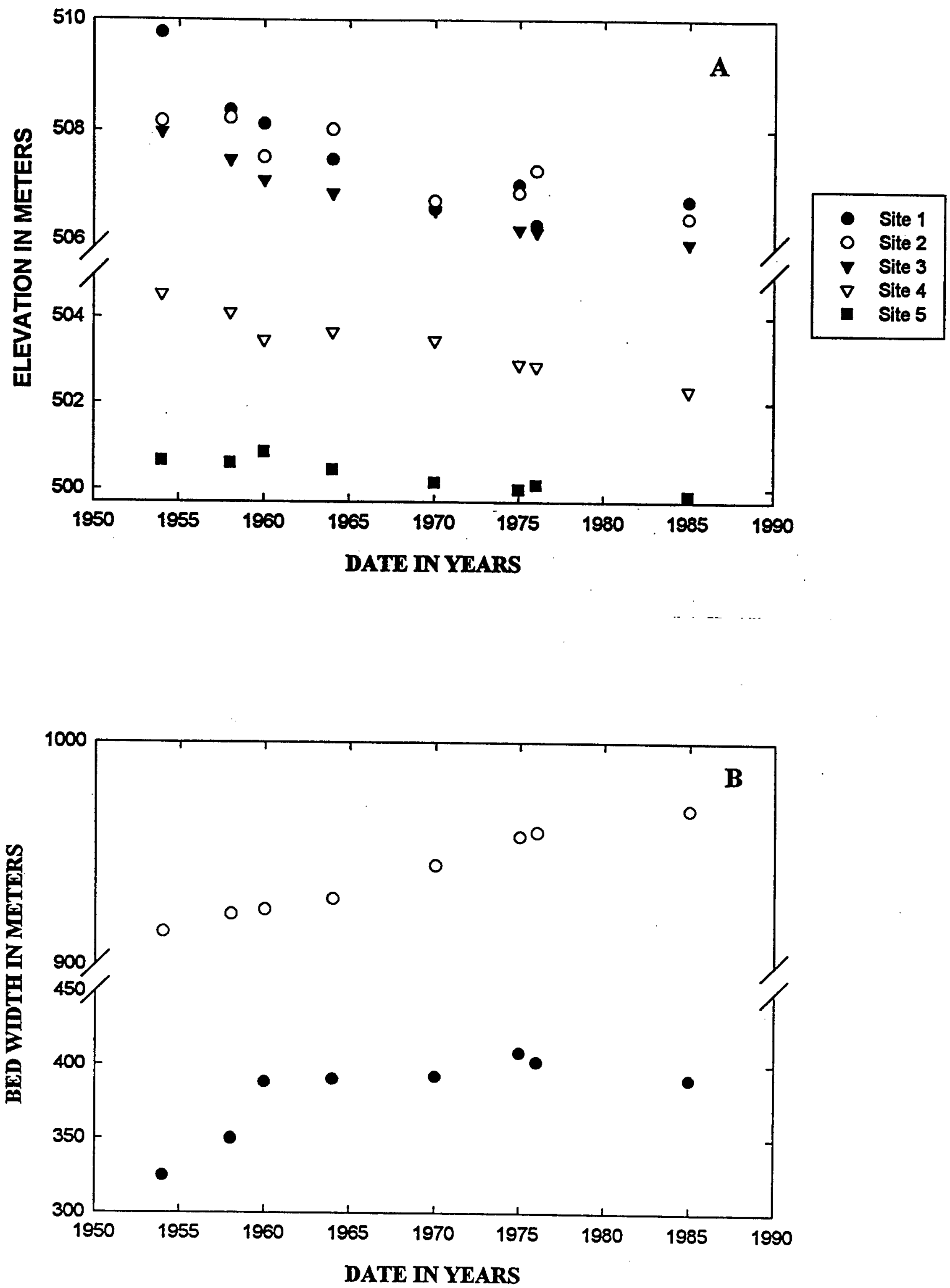

B
Garrison Dam Reach
Width (feet)
Width (metres)
1960 River Mile
1958
1964
1975
1985
PRICE, ND.
WASHBURN, ND.
FT. CLARK, ND.
STANTON, ND.
GARRISON DAM
5 4 3 2 1
1066.75
914.36
761.96
609.57
457.18
304.79
152.39

FIGURE 6



510
508
506
504
502
500
A
ELEVATION IN METERS
1950
1955
1960
1965
1970
1975
1980
1985
1990
DATE IN YEARS
Site 1
Site 2
Site 3
Site 4
Site 5
1000
900
450
400
350
300
B
BED WIDTH IN METERS
DATE IN YEARS

FIGURE 7

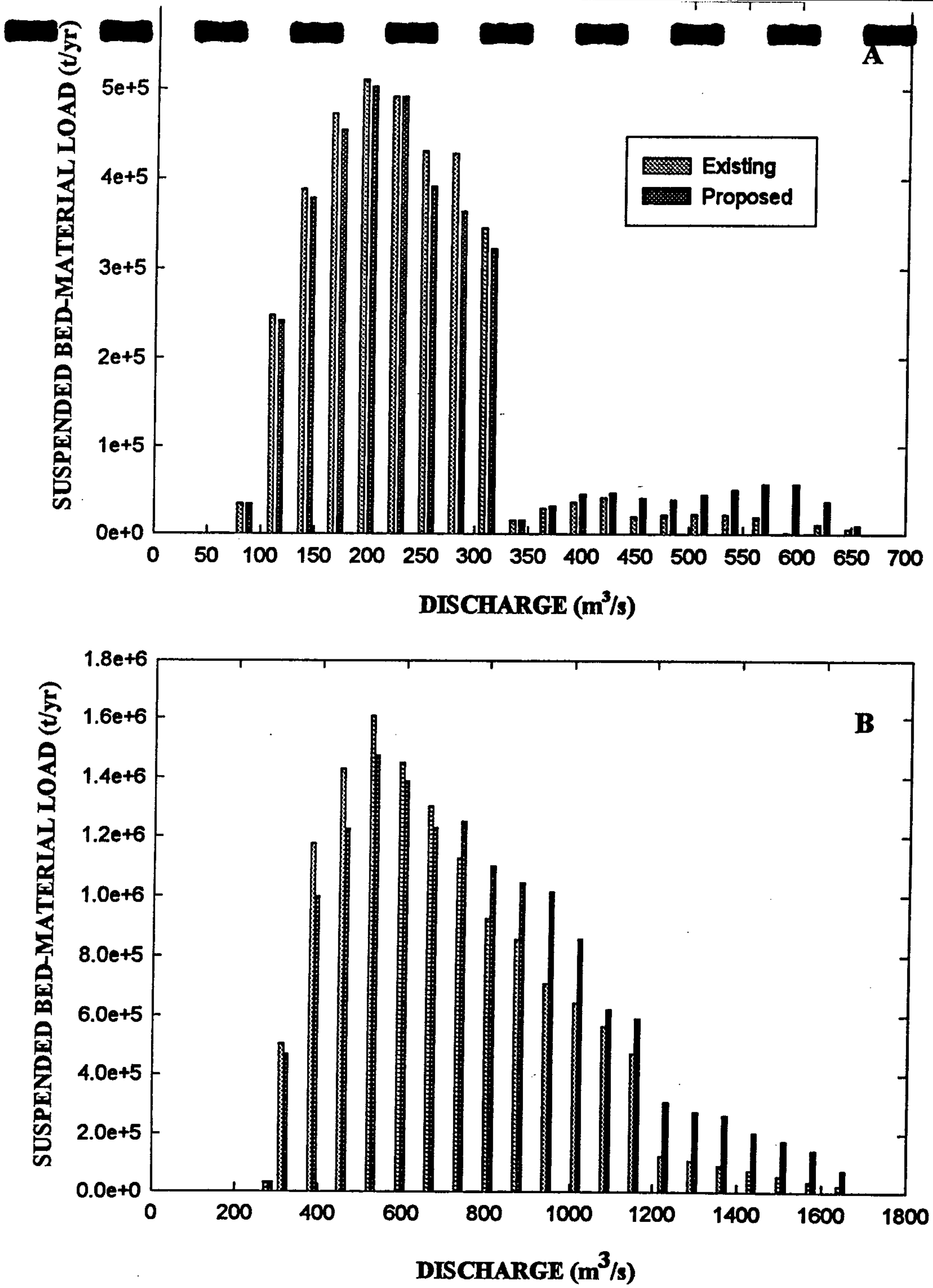
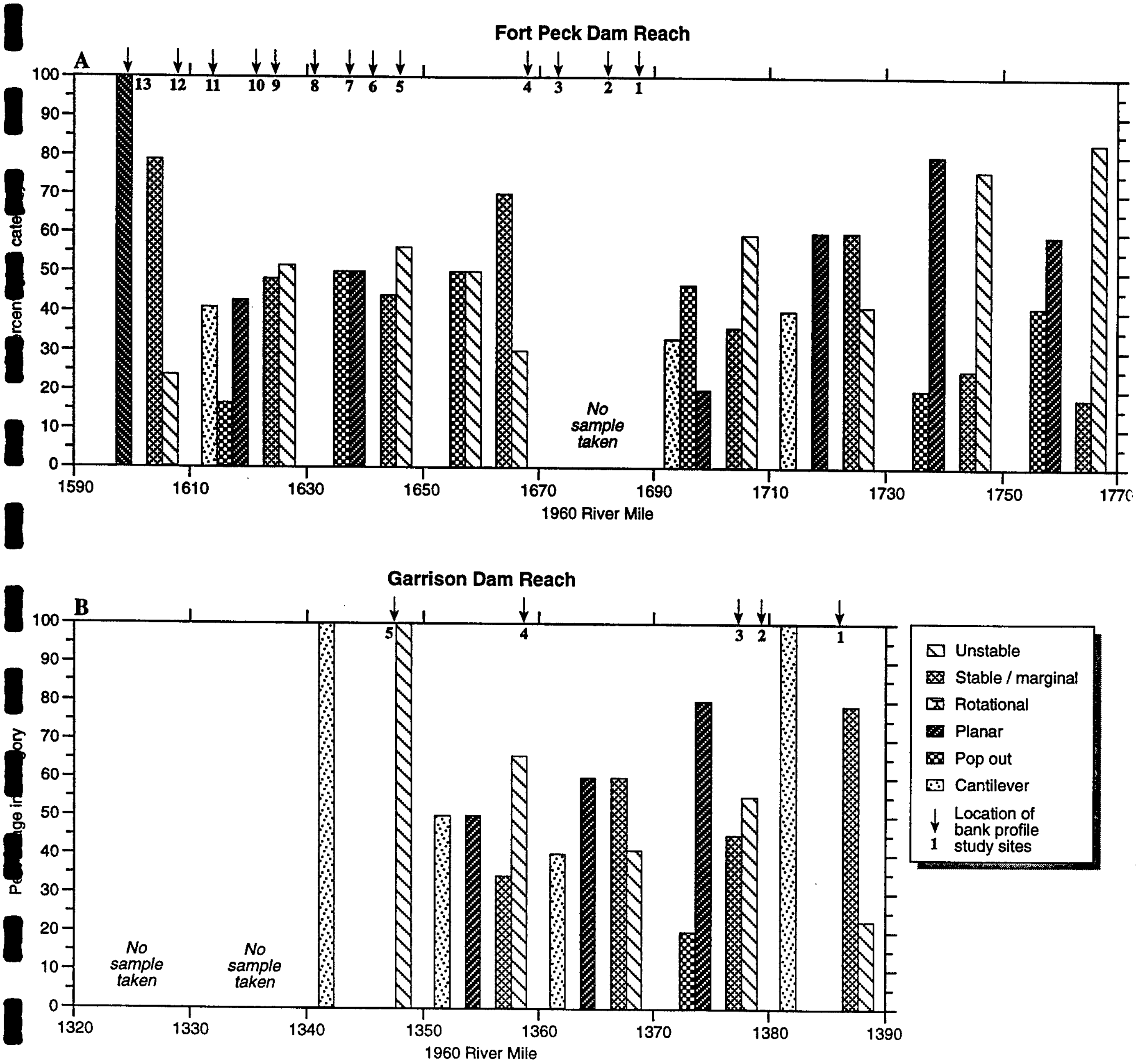

A
B
Existing
Proposed
SUSPENDED BED-MATERIAL LOAD (t/yr)
DISCHARGE (m³/s)
5e+5
4e+5
3e+5
2e+5
1e+5
0e+0
0
50
100
150
200
250
300
350
400
450
500
550
600
650
700
1.8e+6
1.6e+6
1.4e+6
1.2e+6
1.0e+6
8.0e+5
6.0e+5
4.0e+5
2.0e+5
0.0e+0
200
400
600
800
1000
1200
1400
1600
1800

FIGURE 8



Fort Peck Dam Reach
A
13
12
11
10
9
8
7
6
5
4
3
2
1
No sample taken
1960 River Mile
Garrison Dam Reach
B
No sample taken
No sample taken
1960 River Mile
Unstable
Stable / marginal
Rotational
Planar
Pop out
Cantilever
Location of bank profile study sites

FIGURE 9

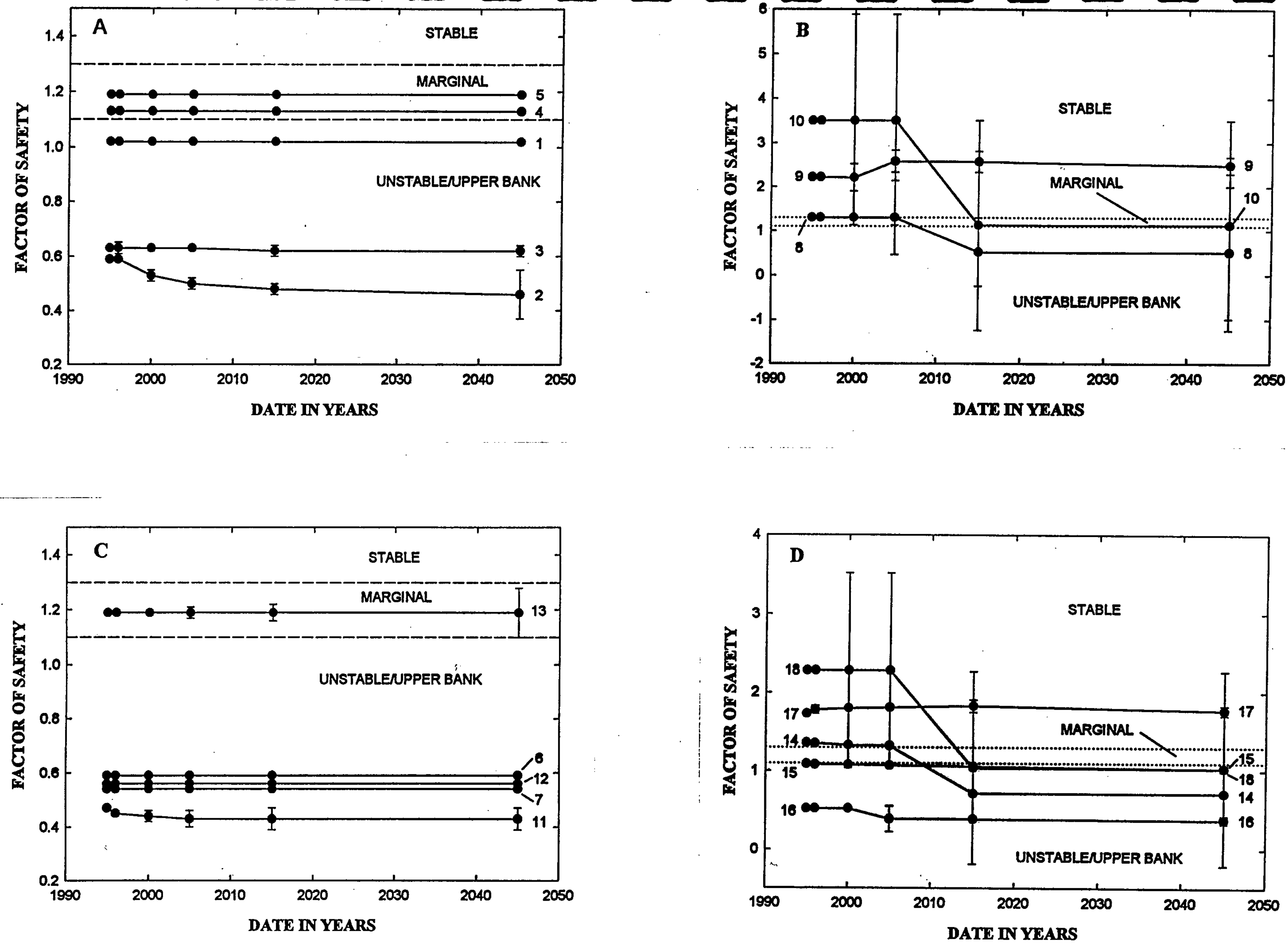

A
STABLE
MARGINAL
UNSTABLE/UPPER BANK
FACTOR OF SAFETY
DATE IN YEARS
1.4
1.2
1.0
0.8
0.6
0.4
0.2
1990
2000
2010
2020
2030
2040
2050
5
4
1
3
2
B
STABLE
MARGINAL
UNSTABLE/UPPER BANK
6
5
4
3
2
1
0
-1
-2
10
9
8
C
STABLE
MARGINAL
UNSTABLE/UPPER BANK
13
6
12
7
11
D
STABLE
MARGINAL
UNSTABLE/UPPER BANK
18
17
14
15
16

FIGURE 10

Plate 1a

Plate 1b

Plate 1c

Plate 1d