

Geomorphological Assessment of Bank Erosion along the Missouri River near Fort Union Trading Post National Historic Site (FOUS) North Dakota – Update Report 2008.
Fort Union Trading Post National Historic Site
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**Geomorphological Assessment
of Bank Erosion along the Missouri River
near Fort Union Trading Post
National Historic Site (FOUS)
North Dakota – Update Report 2008**



Report for the National Park Service

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February 2008



Executive Summary

This report presents the findings of a brief update study an eroding section of the Missouri River at the Fort Union Trading Post National Historic Site (FOUS), North Dakota. The original study was completed in 2005, with a brief update in 2006. This earlier information has also been taken into consideration. The following table provides an outline of this report:

Chapter	Summary
Chapter 1	Introduction to Missouri River and site of problematic bank erosion at FOUS, including project rationale and objectives.
Chapter 2	• Summary of 2005 review of geomorphological effects of ice within rivers. • Review of the effects of ice on the channel morphology, using movie of 2007 ice-out.
Chapter 3	• Summary of 2005/6 findings regarding rates of bank erosion, as measured by NPS employees. • Bank erosion measurements recorded since 2005 also reviewed and assessed.
Chapter 4	• Summary of 2005 description of the planform (overhead view) evolution of the study site and morphology of the site. • Review of planform and morphological change since 2005. • Theoretical model of bank failure at the study site proposed.
Chapter 5	• Discussion drawing together salient points from previous chapters to form conclusions as to reasons for rapid bank erosion at study site. • Conclusions of project and recommendations for further action.
Appendix A	Conclusions, River Management Plan and Soft Engineered Bank Protection Schemes proposed in 2005

This report concluded that, at the time of the study, the erosion of the bank at FOUS did not pose a serious threat to valuable infrastructure, people or property. However, the bank is eroding rapidly and is likely to continue to do so for the foreseeable future. It is, therefore, recommended that a River Management Plan is implemented, as proposed in 2005 (included in Appendix A), especially given the proximity of the bankline to the irrigation ditch along the downstream section of the study reach. This entails continued close monitoring of the site in order to record the rate of erosion.

It should be emphasized that even localised bank erosion must be managed with the recognition that rivers are dynamic, interconnected systems. Given the rate of erosion in recent years, it is likely that bank protection will be necessary in the future, especially along the downstream section of the study reach.

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CHAPTER 1

Introduction

1.1 Project Background and Rationale

The Fort Union Trading Post National Historic Site (FOUS) is situated close to the north (left) bank of the Missouri River, straddling the Montana-North Dakota border (Figure 1.1). The contemporary Missouri is eroding the south (right) bank, encroaching into National Park Service (NPS) land and eroding ancient stands of cottonwood (*Populus deltoides*). This report provides an update to a geomorphological assessment of the bank erosion originally submitted to the NPS in 2005 (Ellis, 2005) and updated in 2006.

It should be noted that this update study is not intended to be an exhaustive assessment.

1.2 Objectives

FOUS superintendent, Andy Banta, has asked for an evaluation of any available new information, in order to complete the following objectives:

- a) Review the ice-out DVD of the Missouri River, captured during the spring of 2007. This DVD has been provided by the NPS.
- b) Review the trend of the erosion measurements provided by the NPS.
- c) Review any other information provided or obtained, including photographs, GoogleEarth images and sketch-maps.
- d) Review the recommendations from the Ellis 2005 report.

This report documents the findings of the new assessment, concentrating on any changes in the pattern and rate of erosion at the study site.

CHAPTER 2

Ice Effects on Channel Morphology, Spring 2007

This section provides a review of the ice break-up during the spring of 2007. Ice-out was captured using a video camera, placed at two different locations. The implications of the processes and morphological change which were captured are also discussed.

2.1 Summary of 2005 Review of Morphological Effects of River Ice

The 2005 report presented a literature review of processes and theories of channel change. This review included a description of the way in which river ice can cause geomorphological change, summarised as follows:

- River ice has a variable and sometimes contradictory effect on the fluvial processes within a river system.
- River ice can form as either:
 - Bank-fast ice, attached to the banks; or
 - Frazil ice, formed as water becomes super-cooled, forming slush and then continuous ice cover.
- River ice generally both forms and breaks-up within the upstream reaches, working downstream (Simon *et al.*, 1999).
- Ice cover decreases channel capacity and changes flow structures. This can lead to elevated flows or bed scour (Zabilansky *et al.*, 1998; Simon *et al.*, 1999).
- Ice break-up (ice-out) is generally the most significant geomorphological processes along cold-region rivers. Ice-out generally occurs episodically due to the formation and break-up of ice-jams. These jams can cause an abrupt rise or fall in water level. Erosion is typically caused by ice gouging or abrasion of the banks, or due to drawdown of water within the banks.

2.2 Ice Break-up Observations

The ice-out was captured using a video camera established at two locations on the bank. The images captured were post-processed to 60 times real-time speed. On some days mechanical failure (most likely due to cold temperatures) prevented capture of video. Unfortunately these days coincided with major erosion events. However, a good deal of information was captured and provided on a DVD. The video was collected and prepared by Dan Licht of the Great Plains Network Ecological Monitoring Program, National Park Service.

- Archos (East) Unit: 5315750 N and 0571730 E
 - 21 March 2007
 - 22 March 2007
 - Large bank failure occurred between 20:00 on 22 March and 08:00 on 24 March
 - 24 March 2007
 - 25 March 2007

- FS-4 (West) Unit: 5316096 N and 0570950E
 - 19 March 2007
 - 21 March 2007
 - 22 March 2007
 - 23 March 2007

Several of the dates were unfortunately unable to be played in their entirety, due to problems with the DVD. However, there was more-than-sufficient video captured to enable a good indication of the ice break-up processes. The important features noted are as follows:

- There does not appear to be any obvious change in stage (water level) over the days captured on video. The discharge records from the Missouri River at Culbertson indicate a gradually falling mean discharge between 19 and 25 March (from 9000 to 6700 cfs).
- The ice cover appeared thin – in some years the ice can reach several feet thick, but in 2007 was probably a few inches thick at most.
- The early coverage saw generally little ice movement, although the ice cover was patchy, with small areas of open water. The amount of moving ice gradually increased throughout the day, but the chunks of ice were small.
- As the ice began to break up, the mobile chunks of ice became larger. The bank-fast ice was the last to become mobile, especially where protected by small embayments in the bankline.
- Along the downstream (eastern) section, a large bank failure occurred, probably on 23 March 2007. This created an embayment in the bankline. Some of the failure mass had been transported away, but much remained at the base of the bank; some as larger failure blocks and some broken down into loose material.
- Along the western section, fine sediment had been deposited at the base of the bank by 23 March 2007. This emphasised the difference in the western and eastern sections: the western section apparently a predominantly depositional reach; with the eastern section actively eroding. This difference is due to the proximity of the thalweg (fastest flow) to the bank. Along the eastern section, the thalweg impinges the bank.
- On 24 March 2007, the river seemed much swifter, with a good deal of mobilised ice. No stationary ice remained. This, therefore, indicated total ice break-up. The moving ice impacted the banks with some force, probably causing abrasion and erosion of bank material. Ice collected within the embayment created by the bank failure. Eddies occasionally caused clear-out of this collected ice, no doubt also causing abrasion of the lower bank and failure blocks. Much of the moving ice appeared to contain sediment particles, and the river water also appeared to be carrying significantly more sediment than on previous days. Appreciable quantities of woody debris was also being carried by the flow, indicating debris clear-out.
- It is interesting that there is no obvious removal of the berm of failure material stored at the base of the bank, yet the greatest rates of erosion occur where the thalweg impinges the bank. It is possible that material is imperceptibly removed from the

berm beneath the water level. This may cause destabilization of the upper bank until it reaches limiting stability. An increase in the saturation levels at this point is likely to trigger failure. Therefore, the material in the apparently unchanging berm may actually be in a state of flux.

Rates of Bank Erosion at the Study Site

Erosion of the right (south) bank of the Missouri River adjacent to FOUS has been causing concern for the NPS for some years. This erosion provided the incentive to commission the initial report. This section provides a review of bank erosion measurements collected by NPS employees since the update report in 2006.

3.1 Summary of 2005 Findings

- NPS employees have been measuring the rate of erosion since 2000.
- Initially, five stakes were placed a distance of 50 feet from the edge of the bank. All five of the initial stakes have now had to be replaced, the new stakes placed a further 50 feet back from the originals.
- Six more monuments were established in 1989, but not regularly monitored until 2002.
- Figure 3.1 shows the position of these stakes.
- The exact location of erosion depends on factors such as the presence of fallen trees or tree roots protecting the bank; the presence of bars within the channel diverting flow towards the bank; and local variability in the geotechnical bank material properties.

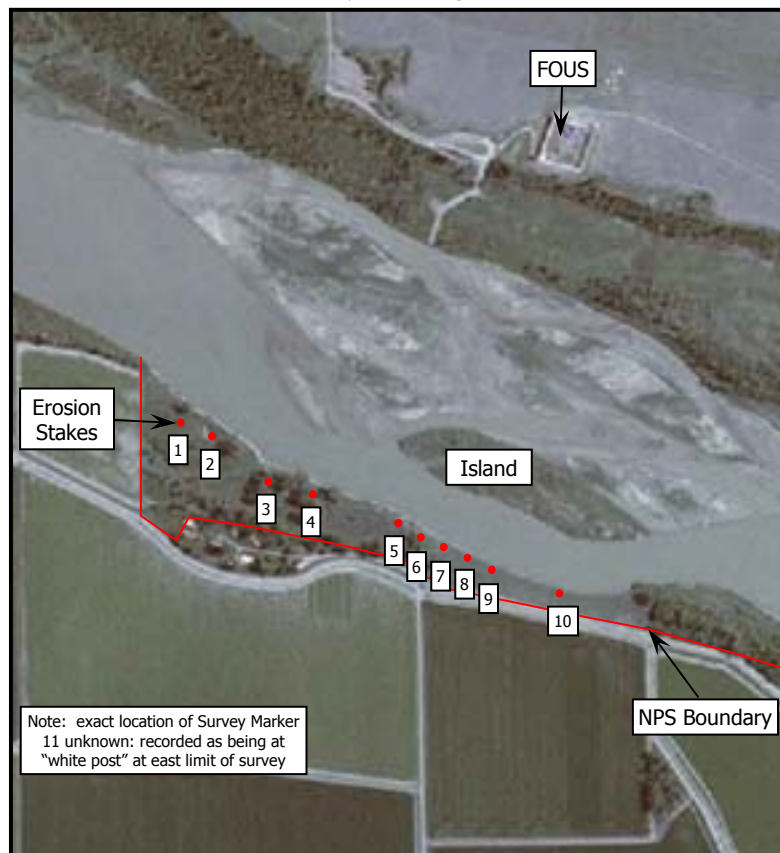


Figure 3.1 Position of Erosion Monitoring Stakes along South Bank of Missouri River. GPS Coordinates Superimposed on 2004 Aerial Photograph. Image Source: NPS Image Collection.

- High rates of erosion occurred at Stakes 6 to 11 between September and December 2002. This may represent the period when the main thalweg channel shifted to the south of the island, causing rapid bank retreat.
- There was a slight correlation between the measured amount of erosion and the discharge magnitude and pattern over the same time period, but only at Stakes 1 to 5. This correlation is not apparent at Stakes 6 to 11, indicating that bank failure is affected by processes other than direct flow entrainment along this section.
- There is no indication that larger amounts of erosion occur during the late spring, due to ice breakup. The rate of erosion at Stakes 6 to 11 may, therefore, be related to the saturation levels of the banks. The diversion of the thalweg around the island, towards this section of the bank may also be responsible for the unpredictable erosion.

3.2 Review of Recent Bank Erosion Measurements

NPS employees have measured the distance between 11 survey stakes and the bankline at irregular intervals (varying between less than a month to 7 months). Since the 2005 report, and the 2006 follow-up, the numbering of the stakes has changed slightly, and this fact should be kept in mind if the different reports are compared. Figure 3.2 shows the position of the stakes, superimposed on the 2007 aerial image of the site.

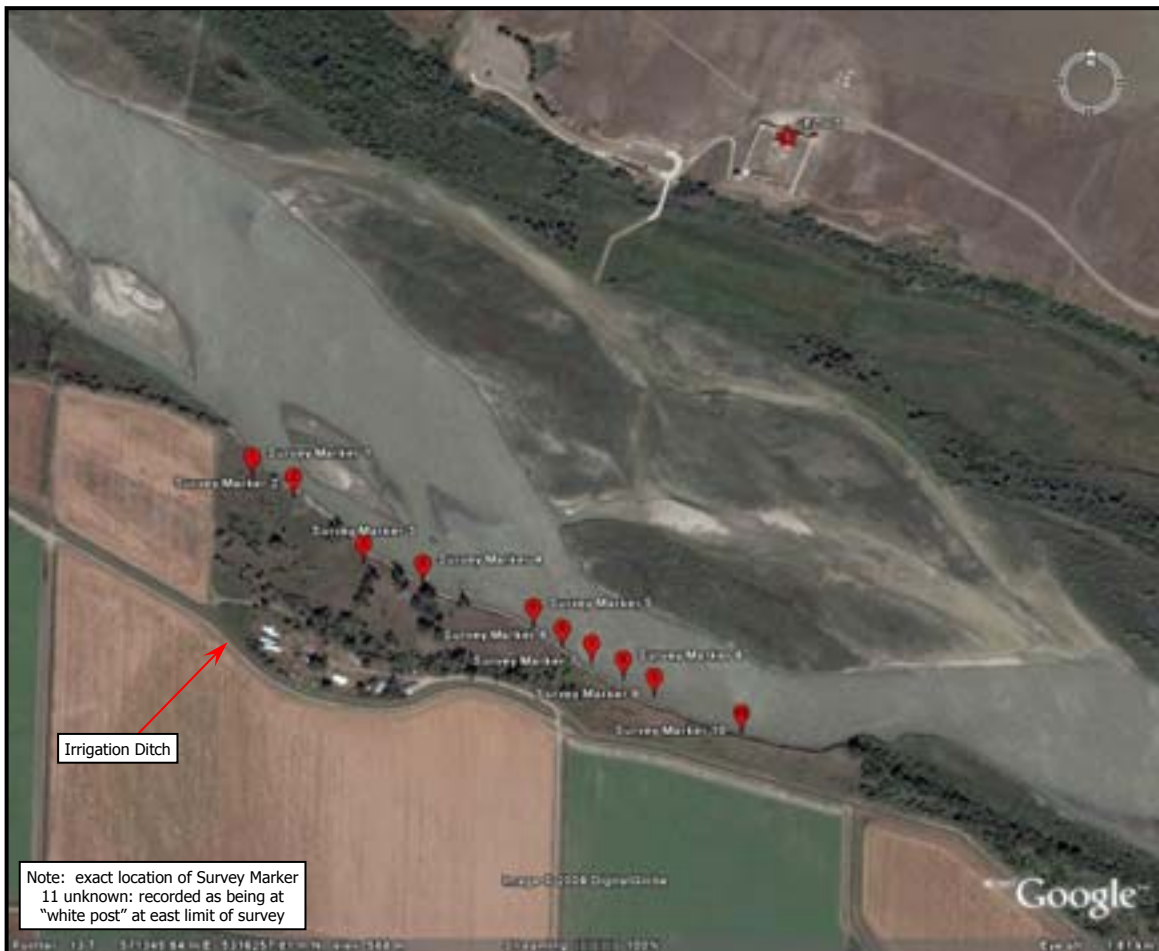


Figure 3.2 2007 GoogleEarth Image Showing Approximate 2005 Position of Marker Stakes (Note Position of Posts Mid-Channel). GPS Coordinates of Stakes Provided by NPS.

The rate of bank erosion has been calculated from the newly provided measurements and is summarised in Figure 3.3a-c and Figure 3.4. Note Figure 3.4 represents the average monthly retreat, and is, therefore, somewhat dependent on the length of time between measurements.

An assessment of the newly measured rates, together with a reassessment of previous measurements was carried out, with the following findings:

- There are three periods of widespread retreat along the study site, with the focus of erosion shifting downstream over the period of record:
 - Between September and December 2002, the upstream section of the bank (between stakes 2 and 6) retreated an average of 15 ft (note that stake 3 retreated by 68 ft between 1989 and December 2002, but has been discounted due to the uncertainty over the timing of this erosion). This erosion appears to have occurred in response to a rapid rise in water level;
 - Between July 2003 and March 2004, the downstream section of the site (between stakes 5 and 9) saw retreat of an average of 14 ft. This seems to have occurred in response to a rapid fall in discharge, which would cause drawdown; a common cause of bank failure;
 - In March 2007, the downstream section (between stakes 6 and 9) again retreated by an average of 14 ft. As in 2004, this erosion appears to have occurred in response to rapid drawdown. Note that there were only 17 days between measurements, hence the seemingly anomalously high amount of retreat shown in Figure 3.4. This suggests that bank erosion occurs both episodically and catastrophically, with periods of preparation, until a threshold is crossed and mass bank failure is triggered.
- The differences in the rate of bank retreat along the study site are not wholly explained by the fluctuation in the discharge of the Missouri River (see Figures 3.3 and 3.4). This indicates that other factors have an important controlling influence on the stability of the bank. These factors include: antecedent precipitation (which can also control the saturation levels of the bank); the effect of river ice; the formation and enlargement of tension cracks; and the presence of vegetation.
- At stake 8, an unusually high amount of erosion, with a retreat of 28 ft, was recorded between Oct 2005 and April 2006. This may represent the failure of a discrete block of bank material, which would form an embayment in the bankline (as discussed in the 2006 update of the original 2005 report). There did not appear to be any trees or similar whose removal would result in this amount of localised erosion.
- The irrigation ditch is now only approximately 130 ft from the downstream section of bankline. The average annual rate of erosion over the period of record for this section (marker posts 6 to 11) is approaching 20ft per year. This is in contrast to the upstream section, which averages only about 7 ft of erosion per year (a not inconsiderable amount). At this rate of erosion, the irrigation ditch adjacent to the downstream section of the study site would be reached within 7 years. This estimate is assuming no major change in planform (which is relatively unlikely, given the dynamicism of the Missouri River).

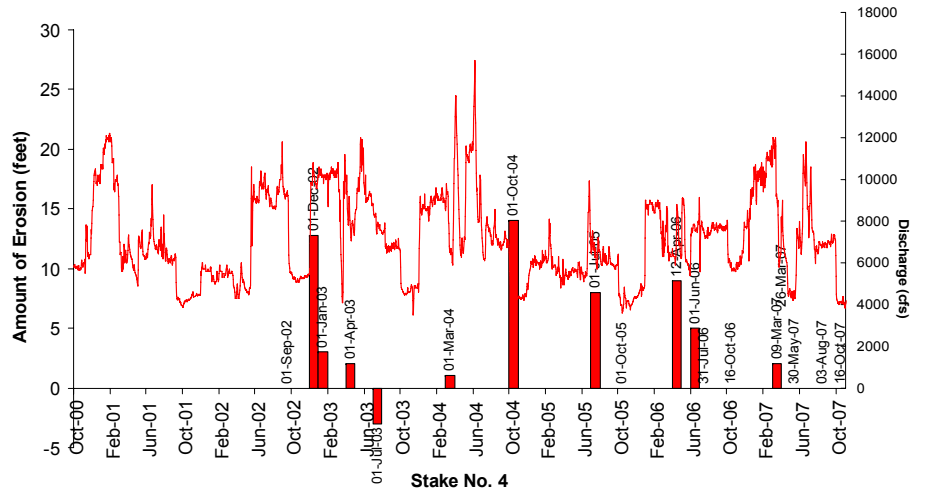
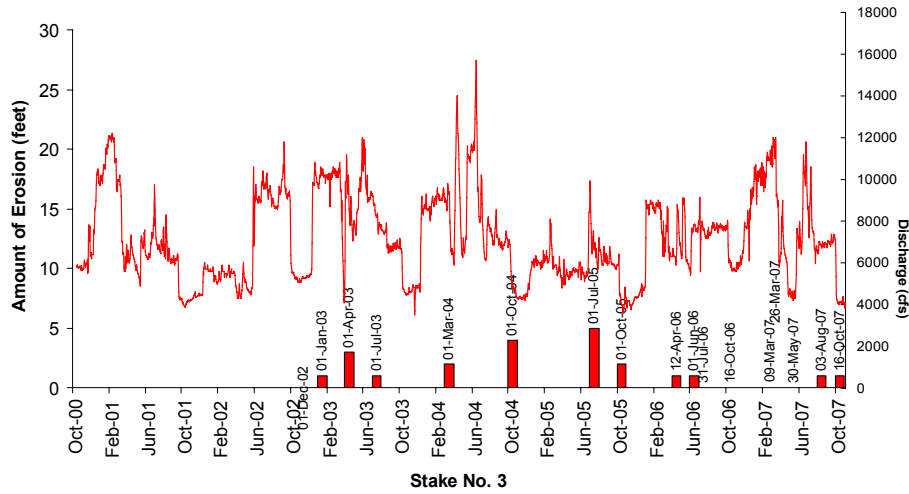
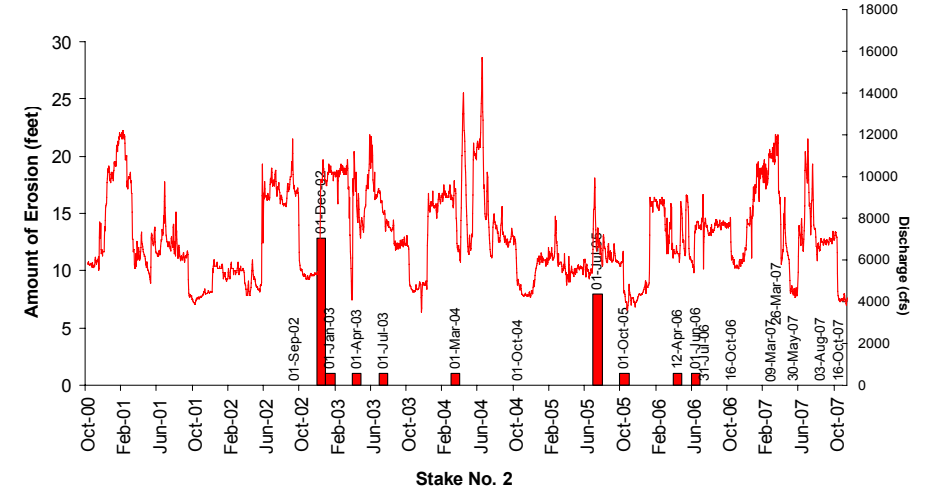
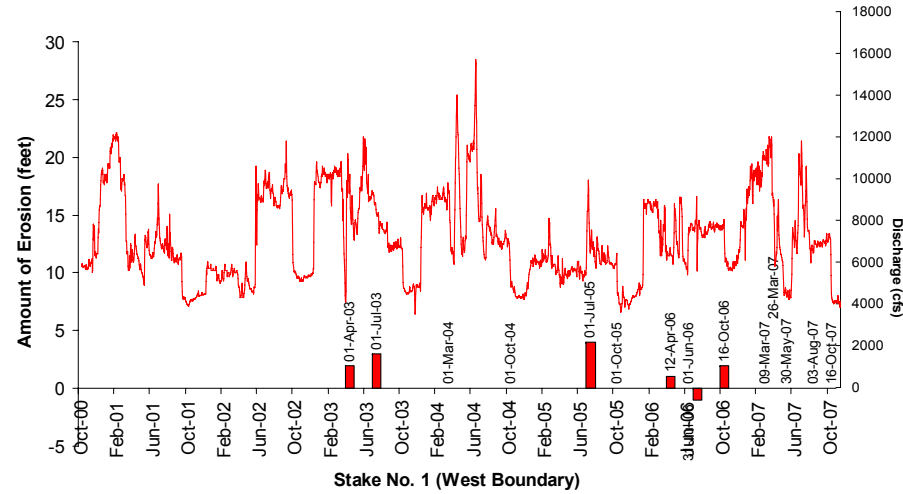


Figure 3.3a Relationship Between Amount of Erosion Measured at Each Survey Stake (feet) and Mean Daily Discharge (cfs) for the Missouri River at Culbertson - Stakes 1-4

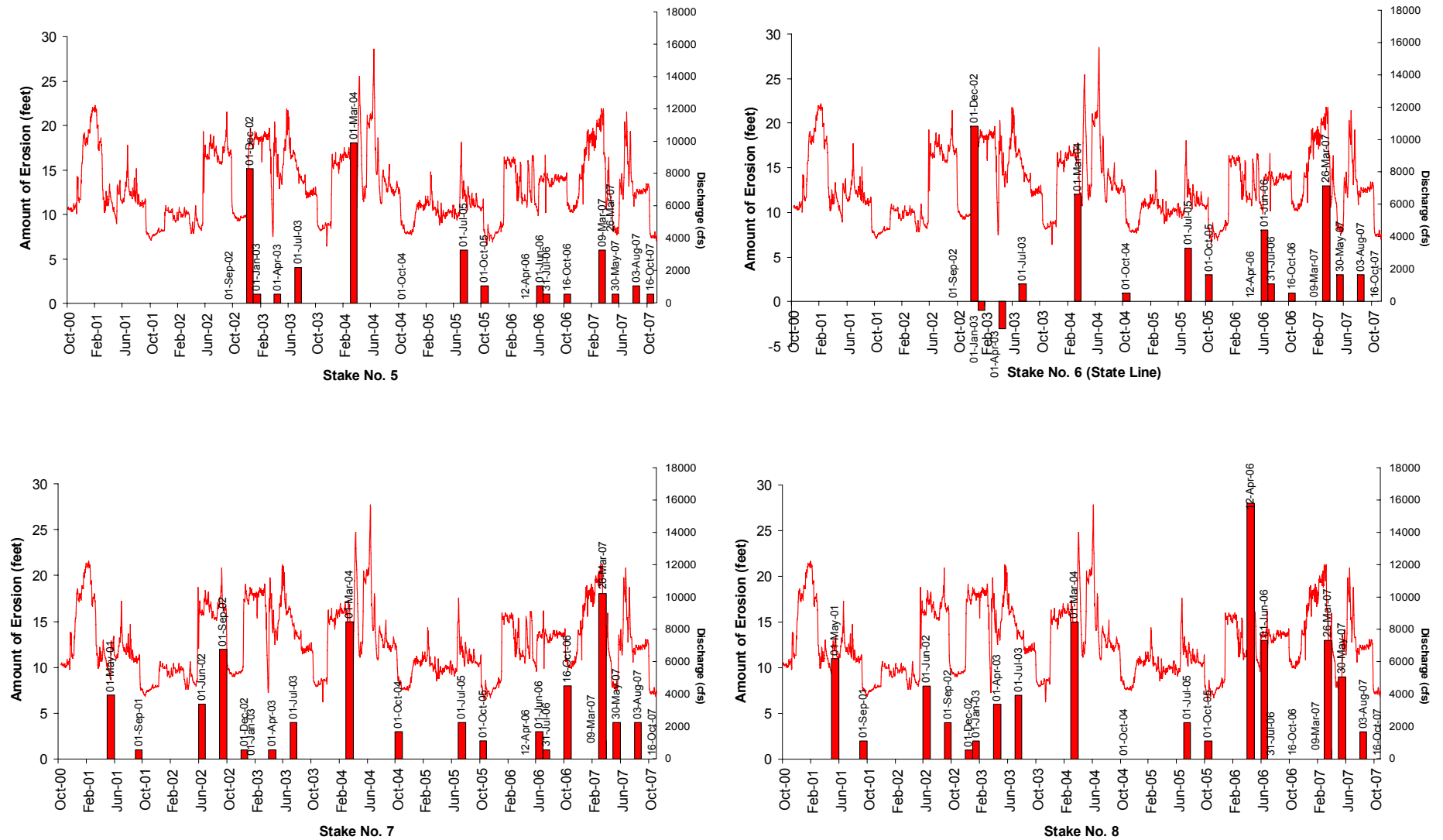


Figure 3.3b Relationship Between Amount of Erosion Measured at Each Survey Stake (feet) and Mean Daily Discharge (cfs) for the Missouri River at Culbertson – Stakes 5-8

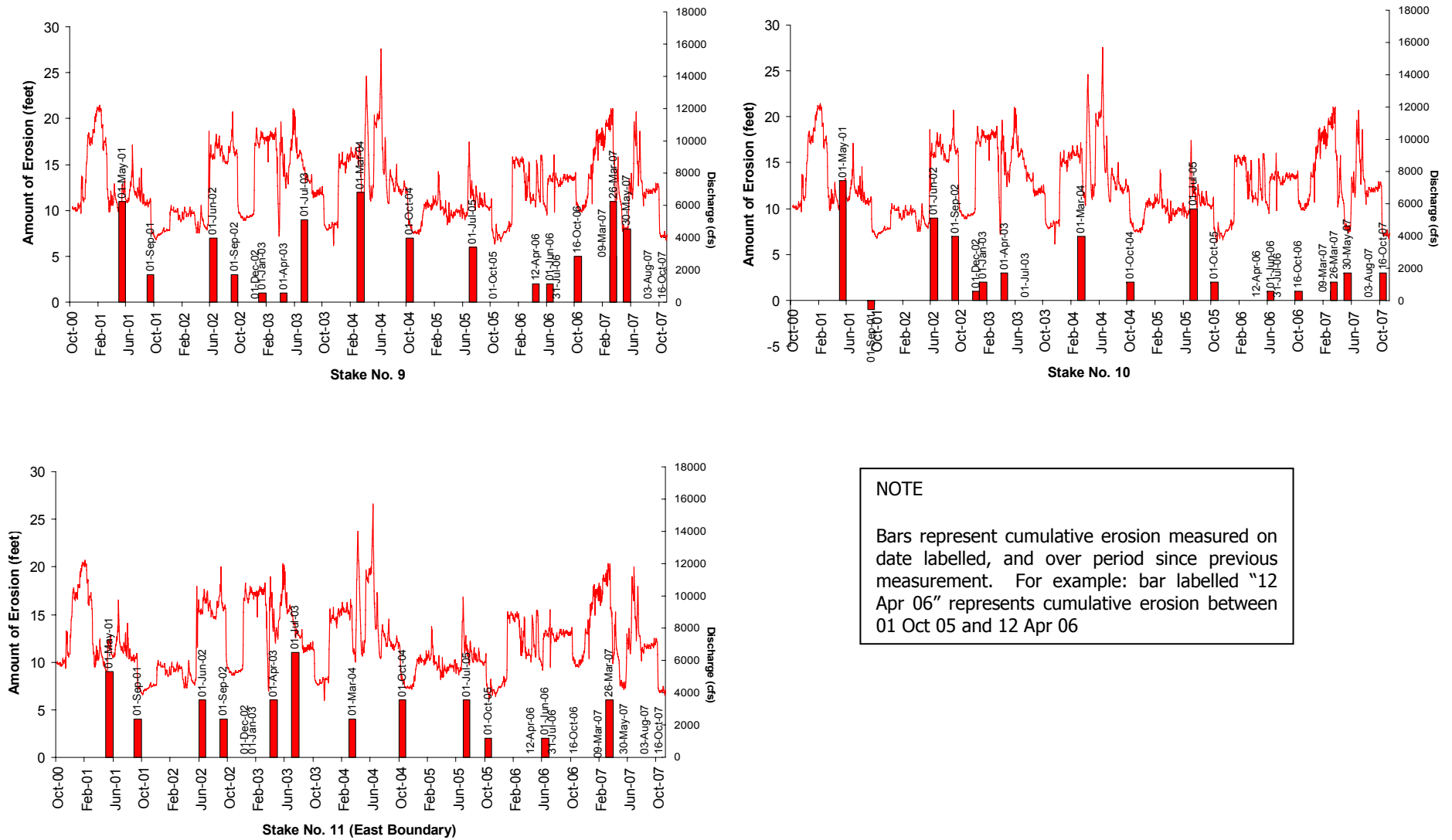


Figure 3.3c Relationship Between Amount of Erosion Measured at Each Survey Stake (feet) and Mean Daily Discharge (cfs) for the Missouri River at Culbertson – Stakes 9-11

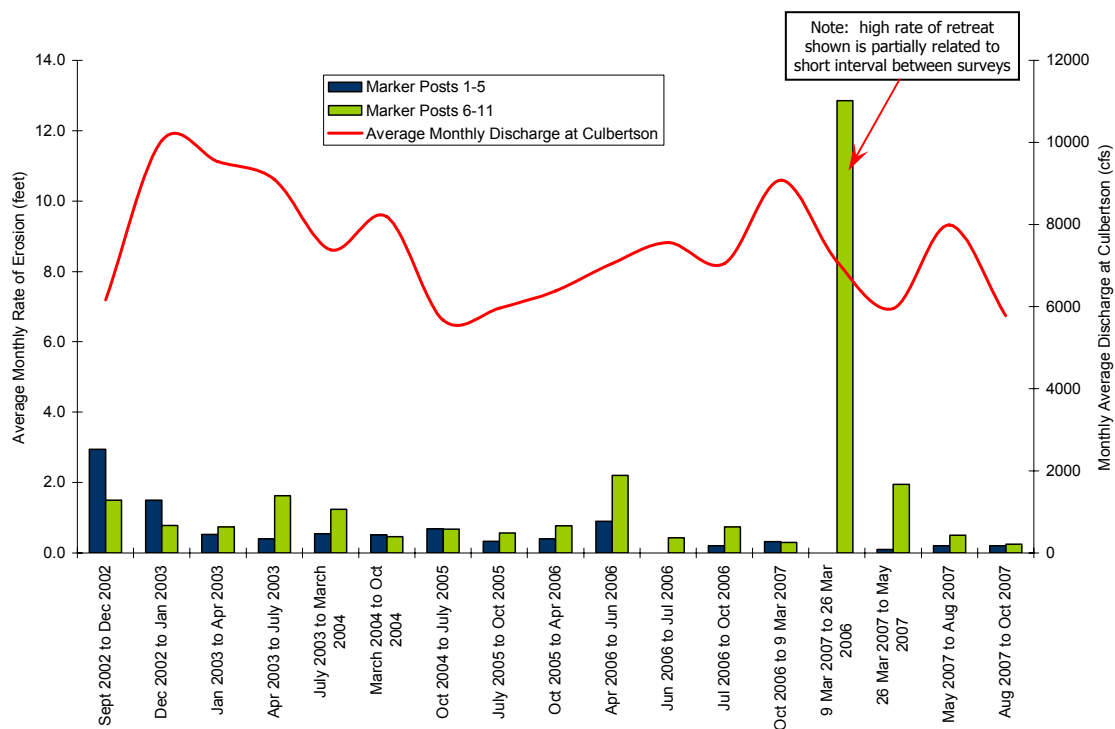


Figure 3.4 Relationship between Monthly Average Rate of Erosion at Study Site and Monthly Average Discharge of the Missouri River at Culbertson. Note that Bars Represent Irregular Time Intervals and are Based on Erosion Measurement Records Provided by the NPS.

CHAPTER 4

Recent Morphological Change at the Study Site

This section presents a review of available information regarding the recent changes in channel morphology at the study site. Aerial images were obtained from GoogleEarth and used to update the 2005 assessment of channel planform change (Ellis, 2005). Ground level photographs were provided by NPS employees. These were also used to provide an assessment of morphological change

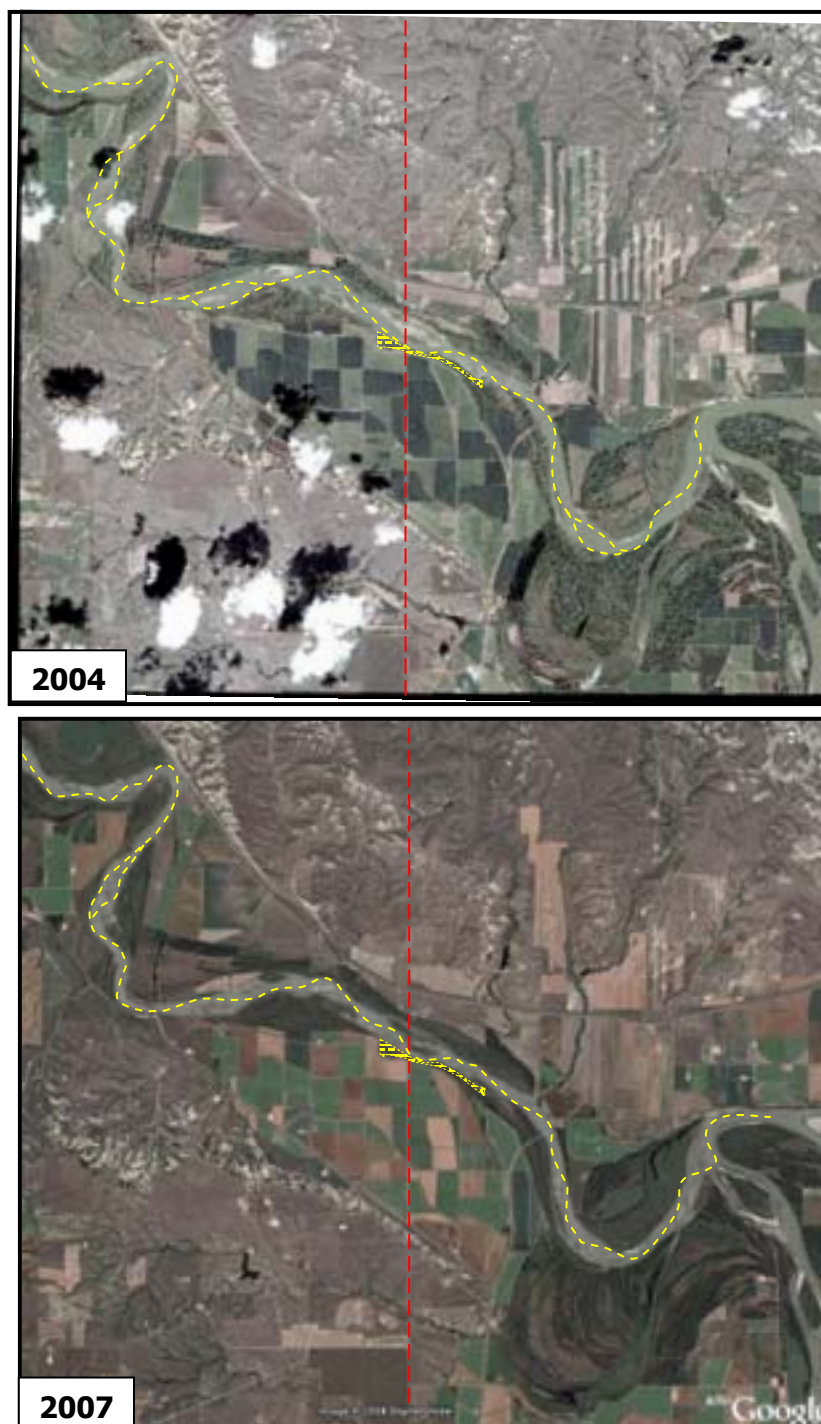
4.1 Summary of 2005 Description of Evolution of the Study Site

FOUS is situated by a relatively straight reach of the Missouri River, just upstream of the confluence with the Yellowstone River and very close to the Montana/North Dakota Border. The remainder of the reach is more sinuous, being confined by Fort Union Sandstone bluffs. Records and maps since the late 1800s has enabled the shifting historic position of the channel to be assessed. The 2005 report presented a review of this information, with the following findings:

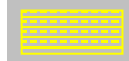
- The main channel through the study side switched from the north (left) to south (right) bank in the mid-1860s. This trend has continued as mid-stream bars have been deposited close to the north bank. Over time, these have become attached to the bank, forming lateral bars, which are eventually stabilised by vegetation. These bars have forced the main channel to occupy a progressively more southerly path.
- The Missouri River is able to rapidly respond to changes in the driving variables of discharge and sediment load. The closure of both Fort Peck Dam, upstream, and Garrison Dam, downstream, significantly affected the morphological development of the study reach.
- The Missouri River is well-adjusted to the variable flow regime, with an active low-flow channel located within the high banks of the sinuous high-flow channel.
- The active channel of the study reach seems to sit on the threshold between a meandering and braided planform. A relatively minor change in the driving variables appears sufficient to cause the planform to change significantly. Rapid changes between single- and multi-thread channels (over the order of one or two decades, or even less) are typical. Equally rapid changes in the sinuosity of the active channel can occur.
- The confluence with the Yellowstone, just downstream, is likely to have an effect on the FOUS reach. It is likely that the changes in dominance are related to the lack of discharge synchronicity discussed in the 2005 Report. When the discharge in the Yellowstone is flooding, it is highly likely that the Missouri backs up, which may affect the morphology of the FOUS reach.

4.2 Recent Planform Change along the Study Site

The planform evolution of the Missouri River, as noted in Section 4.1, was examined in the 2005 report in as much detail as available records would allow. GoogleEarth imagery from 2007 was used to provide information as to the morphological change that had occurred along the study reach, and neighboring reaches, since 2005. This change is shown in Figures 4.1 and 4.2.

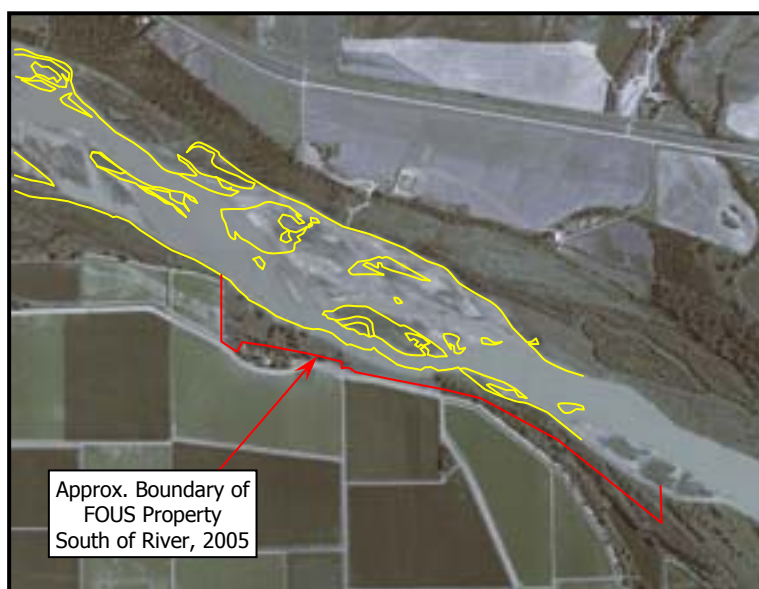


Key To Figure 4.1

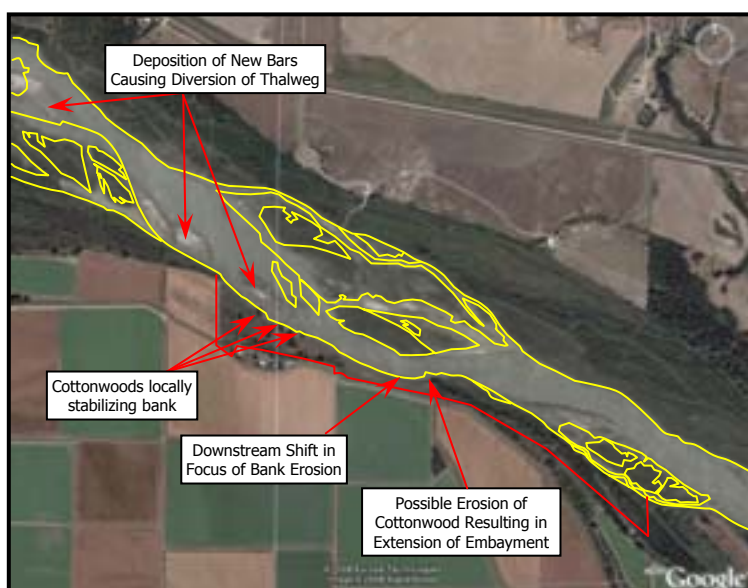
-  Approximate Position of State Line
-  Approximate Position of Thalweg
-  Approximate Position of FOUS Property South of Missouri River

Note: Aerial photographs are not orthorectified. Therefore, this figure is intended only as an indication of channel change. Images are aligned vertically above each other. Please also note potential copyright issues with GoogleEarth imagery.

Figure 4.1 Recent Planform Evolution of Missouri River Study Reach (Image Source: NPS Image Collection; GoogleEarth). It should be noted that there may be copyright issues with GoogleEarth imagery. Therefore, the images contained in this report are intended for internal NPS use only, and should not be published externally.



2004 Image with 1998 Channel Position Superimposed



2007 GoogleEarth Image, 2004 Channel Position Superimposed

Key To Figure 4.2

-  Channel pattern in previous aerial photograph
-  Bar
-  Island
-  Approximate outline of present day FOUS property south of Missouri River

Note: Aerial photograph is not orthorectified. Therefore, this figure is intended only as an indication of channel change. Please also note potential copyright issues with GoogleEarth imagery.

Figure 4.2 Recent Planform Evolution of Study Reach at FOUS (Image Source: NPS Image Collection; GoogleEarth). It should be noted that there may be copyright issues with GoogleEarth imagery. Therefore, the images contained in this report are intended for internal NPS use only, and should not be published externally.

Examination of the images in Figure 4.1 and 4.2 has revealed the following morphological changes through the study reach, and neighboring reaches:

- The channel seems to be switching from a predominantly single-thread channel to a multi-thread channel. A large point bar complex on the inner bank of the upstream meander has become larger, with new bars deposited further out into the channel and also further downstream. This could be occurring due to a pulse of sediment being transported through the system, or in response to varying discharges (as suggested in the 2005 report).
- This increase in the braid index (the number of bars present in the channel) has caused an increase in the sinuosity of the active channel.
- The change in number and extent of channel bars appears to have caused the meander wavelength of the active channel to decrease. This has resulted in a shift in the focus of erosion along the banklines. The deposition of new bars and growth of upstream bar complexes has affected flow patterns through the study site, causing a downstream shift in the locus of bank erosion. Unfortunately, the bank along the downstream section of the study site is closer to the irrigation ditch (in spring 2007, the bank was approximately 130 ft from the ditch). Close monitoring of the position of the bankline should, therefore, continue, in order to assess the risk posed to the ditch.
- The bar complex on the left (north) bank had become stabilised by vegetation. However, extension of the point bar immediately upstream has led to some erosion of the upstream end of the bar complex adjacent to FOUS.
- In several locations along the south (left) bank of the study site, Cottonwoods have continued to locally stabilize the bankline. Opposite, the loss of Cottonwoods at the eastern end of the study site appears to have resulted in the extension of the eroded embayment

4.3 2005 Morphology of the Study Site

The findings of the original 2005 report (Ellis, 2005; and the 2006 update) regarding processes and mechanisms of bank failure along the study site are summarised as follows:

- The exposed vertical banks are mainly composed of sandy material with distinct layering and soil horizons;
- The main mechanism of failure appears to be planar slip failure along tension cracks which develop some distance from the bank edge.
- Almost without exception, the banks along the study reach have a protective berm of failed material at the bank toe. Since this berm does not prevent failure, it is concluded that direct flow erosion cannot be responsible for the majority of erosion. Bank stability must, therefore, be controlled largely by the bank materials and degree of bank saturation; saturation seeming to be the key trigger factor.

4.4 2007 Morphology of the Study Site

Photographs taken by NPS employees on 9 March 2007 support the earlier observations and findings of the bank erosion processes and mechanisms acting along the study site (see Figure 4.3 a-c). These photographs indicate the following:

- Deep tension cracks are shown, indicating the instability of the banks and imminent failure;
- A protective berm of failure material can be seen at the base of the banks, indicating that failure is triggered by processes other than direct flow entrainment;
- Ice has developed at a fairly low water level. However, a considerable amount of erosion noted during ice-out shortly afterwards may indicate ice-damming and rapid



Figure 4.3 Photographs Taken by NPS Employees on 9 March 2007 Shortly before Ice-Out, showing:
a) Deep Tension Crack Approx. 7 ft from Bank Edge;
b) Cantilever Overhang and Recent Bank Failure;
c) Water Flowing from Bank and Recent Bank Failure.

rise and fall of water levels(see Section 3.2). The timing of the erosion certainly indicates that the ice break-up may have been a significant factor in this case.

- Failures again seem to have been triggered by the saturation levels of the bank, with the bank materials providing a contributory destabilising factor. Photograph 4.3c shows water flowing from the base of the bank, indicating high levels of saturation. The high water content of the bank may have been caused by recent prolonged precipitation or melting of ice and snow.

- It has been suggested that water leaking from the nearby irrigation ditch (which is closer to the downstream section of the study reach, see Figure 3.2) could be contributing to the rapid rate of erosion along the Study Site. However, NPS employees have reported that the ditch is dry during the winter (A. Banta, *pers. comm.*, March 2008). This would indicate that the high saturation levels of the bank materials are due to natural factors, such as recent prolonged precipitation; a high or perched water table and/or prolonged high water levels.
- Erosion is predominantly geotechnical (i.e. within the upper bank); with a planar slip failure mechanism. Failures generally occur in discrete sections, forming small embayments.
- Vegetation provides a stabilising influence. As Figure 4.3b indicates, grass roots can bind the upper soil layers, leading to the formation of a cantilever overhang. The stabilising effect of Cottonwood trees has been noted earlier.

4.5 Theoretical Model of Bank Failure at the Study Site

The measured rates of erosion noted in Section 3.2 seem to indicate that episodes of mass bank failure cause an average of 15 ft of erosion. The measurements from March 2007 indicate that failures tend to occur rapidly, with a considerable amount of erosion occurring in a short space of time. Field observations in 2005, and the subsequent photographs provided by the NPS, indicate that tension cracks tend to form between approximately 2 and 7 ft from the edge of the bank (although this statement is based purely on a limited amount of evidence). 15 ft of erosion would, therefore, require multiple, rapid tension crack/failure cycles to occur,

The available evidence supports the statement made in Section 3.2: that bank failures are sporadic and catastrophic. Tension crack formation and occasional basal scour by the river weakens the bank somewhat. Failures are then likely to be triggered when the banks become saturated. Failures occur within the upper bank and in discrete sections, according to the location of the original tension crack. The evidence provided indicates that these localized erosion cycles can occur over a matter of days. However, this must be unusual, otherwise the rate of erosion would be far higher.

CHAPTER 5

Conclusions and Recommendations

5.1 Summary of Report Findings

- A review of the spring 2007 ice-out DVD indicated that, even during a low-ice year, appreciable quantities of sediment are scoured from the banks through the abrasive action of swiftly-moving chunks of ice. Direct entrainment of material can only occur at or below the water-line. However, removal of material from the berm at the base of the bank, combined with saturated bank materials was the likely cause of mass bank failure along the downstream section of the study reach.
- A review of the trend in erosion, using measurements provided by the NPS, revealed that there have been three periods of widespread retreat; in 2002; 2003-4 and in March 2007. Typically, the banks retreated by 14 ft, during a rapid fall in discharge, probably causing rapid drawdown. The data indicates episodic, catastrophic erosion.
- Assuming erosion rates remain constant with those recorded previously, the irrigation ditch could be reached within 7 years. However, the Missouri River is such a dynamic system, that little confidence can be placed in this estimate.
- Photographs and aerial images (taken from GoogleEarth) of the study reach enabled the change in planform since the 2005 report to be examined. The channel through this reach has shown an increase in braid index and sinuosity, resulting in a shift in the focus of erosion along the bankline. As proposed in the 2005 report, this may indicate a rapid planform response to changes in discharge. Since 2005, there has been a notable downstream shift in the focus of erosion at the study site. Unfortunately, this section of the river is closer to the irrigation ditch, and the bankline should, therefore, continue to be closely monitored.
- The stability of the banks appears to be largely controlled by the properties of the bank materials, with high saturation levels seeming to be the trigger for failure.
- The information provided also indicated that vegetation (including Cottonwood trees) provides a stabilising influence.
- The new information provided has indicated that bank failures occur mainly within the upper bank (geotechnical failures), despite the presence of a berm at the toe of the bank. The evidence provided indicates that the banks fail in discrete sections due to tension crack/failure cycles, which can occur over a matter of days. Water flowing from the bank indicated high levels of saturation during March 2007; a period when 14 ft of erosion occurred within a matter of weeks along the downstream section of the study area. The saturation levels of the bank are considered to be one of the key triggers of failure.

5.2 Conclusions

In conclusion, therefore, the new information provided by the NPS has provided support for the conclusions reached in the 2005 study: most importantly, that monitoring of the rate of erosion should continue, and the banks protected if the rate of erosion increases, or the irrigation ditch is threatened.

Since 2006, erosion along the southern (right) bank of the Missouri River opposite FOUS has continued. Erosion rates are higher along the downstream section of the reach. This pattern of erosion appears to have occurred in response to the changing planform of the river. The increase in sinuosity and braid index over the past couple of years has caused the focus of erosion to shift downstream.

The ice-out DVD provided evidence to support the belief that river ice is a significant geomorphological agent, even during a relatively low-ice year. Over the period of study, since 2005, the greatest amount of erosion occurred during 2007 ice-out, within the space of a few weeks.

5.3 Suggestions and Recommendations

- Erosion of the south (right) bank opposite FOUS is continuing. Monitoring of the rate of erosion should, therefore, also continue. The changes to the marker post numbering seem logical, and it is recommended that this numbering remains in use.
- NPS employees at FOUS could also keep a record of the date and approximate location of failures, when/if they are noticed. Therefore, even if there is not time or resources for a full survey, data recording the seasonality and location of erosion could still be recorded. This data could then be compared with quantitative survey data.
- Since the bank is only approximately 130 ft from the irrigation ditch at present, with average annual rates of erosion approaching 20ft along the downstream section, it is recommended that the River Management Plan proposed in 2005 (included for Reference in Appendix A) should be followed. Design of a bank protection scheme could prove prudent, in order for implementation:
 - Plans for bank protection measures could be drawn up, should the bank reach, for example, within 60 ft of the irrigation ditch ("Amber Zone"),
 - These plans would then be ready for implementation if the bankline reaches 45ft from the ditch ("Red Zone").

There is, however, a distinct possibility that the erosion trends over the next decade or so could change, given the highly dynamic nature of the Missouri River.

- The NPS has requested recommendations for the useful location of wells to determine the hydraulic connectivity between the irrigation ditch and the bankline. Given the proximity of the irrigation ditch to the bank along the downstream section of the study site (marker post 6 onwards), it would seem logical to concentrate the wells in this area. Depending on the number of wells allowed for, ideally at least one well should be sunk along the upstream section, preferably in a section without large trees (such as near Marker Post 3). This area may be affected by the buildings near the irrigation ditch). Along the downstream section, it is recommended that two sets of two wells, each perpendicular to the bankline, are sunk. A suggested location for these holes is between Marker Posts 9 and 10, and then downstream of Marker Post 10. When reviewing the well level findings, the following factors should be taken into account:
 - Precipitation;
 - Flow levels in the Missouri River;
 - Water levels in the irrigation ditch;
 - The inter-connectivity between water levels in adjacent wells;

- Water flowing from the banks;
- If possible, the direction of groundwater flow should be recorded.

However, given the findings of this report (that large amounts of erosion can occur when the ditch is dry), it is unlikely that water from the irrigation ditch significantly affects the stability of the bank through the study site: it is more likely that the stability is controlled by the bank materials/composition, bank saturation levels and the flow dynamics of the river.

- A key finding of this report is that high bank saturation levels are the most likely trigger for bank failure along sections of the bank that are at limiting stability. Therefore, any future bank protection design schemes must include drainage control measures. This will ensure that a build-up of pore-water pressures behind the bank protection is avoided.
- In order to determine whether bank protection is implemented, FOUS and NPS employees need to decide how important the bankline and land south of the Missouri is. As the findings of this report have indicated, rivers constantly change, and the erosion is part of the natural cycle of events.

Given the above, it is, therefore, recommended that the following course of action is taken:

- Continue to monitor the rate of bank retreat and pattern of river change, to determine trends and predict likely future change;
- Decide how important the land and assets which could be potentially affected by the erosion are;
- If/when the bankline reaches the “Amber Zone”, and the land/assets are thought to be sufficiently valuable to warrant protection, begin to liaise with bank protection specialists.
- Information regarding the geotechnical properties of the bank materials; the water table level (and presence of perched water tables) and the likely forces acting on the bank (such as the abrasive action of river ice), as described in Appendix A, could be required;
- Ensure that bank protection measures take the processes and mechanisms of erosion into account, and are designed to allow water to drain freely from the bank. This will ensure that the design is appropriate for the conditions at the study site, and will be sustainable and effective (as outlined in Appendix A);
- Implement the bank protection scheme when the bankline reaches the “Red Zone”, again assuming that the decision has been made that the land and assets warrant protecting.

References

- Ellis, L.A. 2005. Geomorphological Assessment of Bank Erosion along the Missouri River near Fort Union Trading Post National Historic Site (FOUS), North Dakota. Report for the National Park Service. Updates in 2006 and 2007.
- Simon, A., Shields, F.D., Ettema, R., Alonso, C., Mashall-Garsjo, M., Curini, A., and Steffen, L. 1999. Channel Erosion on the Missouri River, Montana between Fort Peck Dam and the North Dakota Border. USDA-Agricultural Research Service.
- Zabilansky, L., Ettema, R., Yankielun, N., and Weubben, J. 1999. Survey of River-Ice Influences on Channel Stability along the Fort Peck Reach of the Missouri River, Montana, Winter 1998-1999. US Army Corps of Engineers, Omaha District Executive Summary.

Appendix A: 2005 Conclusions and River Management Plan

This Appendix presents the conclusions, River Management Plan (including recommendations for soft engineered bank protection) and possible funding sources, for reference. All literature references may be obtained from the original report.

A1.1 Conclusions of 2005 Report

- a) Following the closure of Fort Peck Dam, degradation of the Missouri River occurred in response to the reduced sediment load. The increased supply of sediment caused aggradation of the downstream reaches. This aggradation continued due to rising reservoir levels as Lake Sakakawea filled behind Garrison Dam
- b) Regulation of the Missouri River after dam closure has caused the hydrograph of the Missouri to become less extreme, with reduced peak and increased average discharge magnitudes. The reduction in geomorphologically effective peak flows, in particular, has affected the morphology of the Missouri. The seasonality of peak flows has also been changed significantly from late spring to February/March, increasing the level and, therefore, extent of river ice erosion. The change in timing of flood peaks has also caused a lack of synchronicity between peaks in the Missouri and Yellowstone Rivers. The exact morphological response to the resultant backwater effects along the study site are unclear.
- c) The change in system drivers has caused a significant change in aquatic and riverine habitat, which has caused several fish and bird species to become threatened or endangered.
- d) The study reach has a low-sinuosity braided channel. Immediately after dam closure, the braid index increased in response to the higher sediment load input from the degrading reach. As the load decreased due to the reestablishment of quasi-equilibrium in the upper reaches, the study reach became more sinuous, with fewer bars. The contemporary channel is virtually single-thread, with a sinuous thalweg.
- e) The main thalweg channel along the study site has been migrating south since the mid-1800s. This is due to planform evolution through this reach: mid-stream bars form towards the north of the channel, becoming attached to the north bank over time. This causes the main channel to become diverted further south, eroding the south bank. This planform change has resulted in the creation of a meandering thalweg, increasing the rate of erosion at the study site. The wavelength of this active channel has shortened, causing sections of the bank that were previously untouched to begin eroding.
- f) The main process causing erosion at this site is likely to be gouging and abrasion of the banks by river-ice during spring break-up. The process is more effective if the banks are saturated. Even without the scouring effect of ice, saturation of the bank materials after prolonged precipitation events is also likely to contribute significantly to instability. Both processes act along the upper layers of the bank, negating the stabilizing effect of the vegetated berm along the base of the bank.
- g) The rate of bank erosion is relatively rapid, with up to 60 feet of erosion occurring in the last five years. The cross-sectional morphology of the bank indicates a stable morphology, with a low-angled, vegetated berm at the base of the bank. However, the presence of tension cracks and recent failures above this berm suggest that the saturation levels of the bank are the most important factors determining bank

stability. Failures are likely even when the vertical free-face is not attacked directly by the flow. The rate of erosion is also determined by the frequency of basal clear-out of failed material.

- h) It is recommended that bank stabilization is not appropriate at the moment due to the low intrinsic value of the land being eroded, together with the cost and potential impact on the channel morphology. However, close monitoring of the site should continue, as detailed in Section 5.3.
- i) It would be prudent to continue investigation of suitable bank protection measures, in the eventuality that the rapid rate of erosion continues or the nearby irrigation ditch is threatened, especially given that it may take time to secure funding for any scheme proposed. Soft bank protection schemes, such as the implementation of fiber matting capable of withstanding shear stresses due to ice scour, should provide the most suitable and effective results.

A river management plan has been proposed based on the findings of this investigation.

A1.2 2005 River Management Plan

It is important to stress that a natural system always changes in response to fluctuations in the system drivers – and these drivers never remain static but are in a constant state of flux. Therefore, river systems are also in a state of flux as adjustments are made in response to the variability in inputs, in an attempt to maintain quasi-equilibrium. The contemporary Missouri River is evolving in response to the construction and closure of several major main-stem dams. If left to adjust naturally, quasi-equilibrium will eventually be attained. In many reaches of the contemporary river, this has already occurred. It is vital that any management plan take this into consideration. Implementation of stabilization should hasten equilibrium, rather than creating requiring further major system- or reach-scale morphological adjustments.

The major issue surrounding contemporary river management plans is the local perception that erosion is always negative or harmful and should be prevented. Since rivers, by their very nature, always erode their banks, the river manager should determine whether proposed stabilization schemes will have a positive impact on the natural system, as well as protecting the threatened land. The impact of a project on the up- and downstream reaches should always, therefore, be considered.

The following points should also be considered:

- One of the major reasons for this investigation was to determine the possibility of regaining the former scenic and historic quality of the view from FOUS. Rather than attempting to alter the position of the Missouri back to its historic mid-1800s position, it may instead be more practical to provide tourists with some education about the dynamic nature of the river. An interpretive panel overlooking the study reach could be put in place, informing visitors about the southerly migration of the channel, especially given the role of this shift in the abandonment of FOUS. Aerial photographs, such as those used in Figure 4.1 could be used to illustrate this.
- At the present time, although land and trees are being lost to the river, bank stabilization measures are, in all probability, not cost effective due to the low monetary value of this land. However, if the rate of erosion becomes more rapid or

structures, such as the nearby irrigation ditch, are threatened, bank stabilization may be required.

- It is strongly recommended that the rate of erosion is closely monitored. It would be beneficial to carry out field measurements at regular intervals, for example every three or four months. This would enable the seasonality of the erosion to be examined, which would further the understanding of processes and mechanisms acting on the bank. It would be useful to establish the exact causes of bank retreat at this site, rather than relying on conjecture. This would enable a more suitable bank stabilization scheme to be designed, if required.
- When surveying the bank to determine the amount and rate of erosion, stainless steel stakes, such as those already in place, should be used. However, two monuments should be utilized if possible, so that the same line of measurement is used each time. Cross-sections are generally surveyed perpendicular to the channel centre-line. This enables direct comparison of bank erosion rates. GPS is a useful tool for locating rebar, but is not generally accurate enough to measure small changes in the position of the bank. It would be beneficial to use surveying equipment, rather than a tape measure, as tape measures are prone to stretching or bowing if used over long distances.
- Although it is not recommended that a stabilization project is implemented at this time, consideration should still be given to the type and location of possible bank protection measures. The chosen scheme could then be rapidly implemented if erosion continues unabated.
- Care should be taken when designing a bank stabilization scheme that the local fluvial and climatic conditions are taken into consideration. Literature documenting the success or otherwise of other schemes should be reviewed with this in mind. In particular, the effect of river-ice on bank protection should be investigated prior to finalizing a design. In general, bank protection schemes concentrate on protecting the bank toe, which typically controls the rate of erosion. However, along the study site, it is possible that ice scour and weakened bank materials (due to saturation) may cause instability at the top of the bank despite the protective, vegetated berm. It is vital, therefore, that any bank protection scheme design takes this fact into consideration. Lack of protection along the upper bank may result in bank toe protection being eroded out from the back or flanked, ultimately resulting in failure.
- Prior to implementing any bank stabilization scheme, a full analysis of the geotechnical properties of the bed and bank materials should be undertaken to determine the stable geometry for design purposes.
- Any bank stabilization scheme implemented will affect the neighboring reaches. To avoid simply shifting the locus of erosion to a different location, care should be taken that the system dynamics discussed in this report are considered.

The USACE are currently contemplating revising the timing of releases from Fort Peck Dam in order to create a more natural hydrologic regime. This may prove crucial to the restoration of the natural habitat of indigenous species, in particular, the pallid sturgeon. If this occurs, the dynamics of the study reach may change in response to this alteration. A test release giving a flow magnitude of 15,000 cfs over a four week period was planned for June 2002 (USACE, 2002). This is well within the regulated range of flows which normally occur. However, a drought has occurred since then, which has

prevented this test from being carried out. The change in hydrologic regime will not, therefore, be implemented in the near future.

A1.3 Suitable Bank Protection Schemes

The USACE have constructed a number of erosion control projects along the reach between Fort Peck Dam and Garrison Dam. These were implemented under Section 32 of the Flood Control Act of 1974, Public Law 93-251 (Mellema, 1997). Section 32 programs were authorized particularly to maintain natural riverine characteristics, minimize environmental degradation of the fluvial environment. Structures were, therefore, kept as low as possible, without constricting the river channel. Local land owners are now required to use materials other than riprap to protect their property (although in apparent contradiction to the natural ethic, car bodies are considered acceptable). In addition, Section 33, or “soft” projects were also implemented, which used bank stabilization methods utilizing natural, readily available materials. Both projects were not designed to halt erosion entirely, but instead to keep the loss of agricultural land to a minimum.

Concern has been raised over the ability of stabilization measures to withstand ice erosion, especially in the case of the soft schemes. The rapid stage fluctuations caused by the formation and break-up of river ice may have adverse effects on these structures (Zabilansky *et al.*, 1999). Stabilizing vegetation and construction materials may be plucked by the abrading and gouging effects of the ice. Quantitative measurements evaluating the impact of ice on bank protection schemes are unavailable. However, historic observations have indicated that riprap able to withstand design flow events will withstand shear stresses due to ice scour (New Brunswick Sub-Committee on River Ice, 2000). Ice formation may also cause flows to be concentrated *towards* rather than *away* from the banks due to the alteration of flow patterns around weirs and dikes (Zabilansky *et al.*, 1999). Bank protection schemes may also cause a widened belt of bankfast ice, thus increasing the shear stress on the bank. The steeper the bank, the narrower the strip of bankfast ice required to maintain stability (Ettema, 2001). Stabilization measures which protrude into the channel should, therefore, take this fact into account and the design should include shorter, closer structures (Zabilansky *et al.*, 1999).

Mellema (1997) provided a comprehensive review of the impact of varying types of implemented bank stabilization schemes along the Upper Missouri and their success, summarized as follows (Table 5.1):

Table 5.1 Effectiveness of Different Types of Bank Stabilization Along the Upper Missouri River (After Mellema, 1996).

Project Type	Description	Performance
Section 32 Projects		
Windrow Revetments	Stone fill placed in an excavated trench (a natural scour hole if possible) along the top or base of a bank, where erosion causes the stone to fall and protect the bank material.	• Met or exceeded expectations • Should not be used in banks over 15 feet high • Safety hazard due to loose material on bank surface
Composite and Reinforced Revetments	Stone placed along the lower portion of the bank to prevent undercutting.	• Very reliable if adequate toe protection is used for the anticipated amount of scour • Erosion downstream highly likely

Table 5.1 Effectiveness of Different Types of Bank Stabilization Along the Upper Missouri River (After Mellema, 1996).

Project Type	Description	Performance
Hard Points	Short spur dike extending perpendicularly into the channel.	• Need to be placed and designed with caution • Eddy scour extremely likely • Should only be used along low/mid bank heights and straight/convex banklines
Refusals	Stone fill tie-ins excavated into the bank at the upstream end of revetments to prevent outflanking.	• Buried stone fill, rather than Windrow-type, should be used if considerable erosion is anticipated • Wide cross-section is recommended
Vane Dikes	Stone-fill ridge placed in the channel, not tied into the bank.	• Used where the river was attempting to occupy a new channel, eroding additional sections of the bank • Not recommended as a stand-alone erosion control measure • Boat hazard • Useful for creation/preservation of sand bar habitat
Earth Core Dikes and Channel Blocks	Local sand or earth used as core, with more expensive stone on upstream and river-ward end. Similar to Vane Dikes, but attached to bank and earth core.	• Used where the river was attempting to occupy a new channel, eroding additional sections of the bank • Should be constructed with through-pipe to maintain downstream habitat diversity • Downstream deposition prevents recreational use • Major impact on channel
Section 33 Projects		
Log Hardpoints and Log Cribs	Similar to traditional hardpoints but using bundles of logs.	• Little or no flexibility to respond to fluctuating conditions • Stone at the base, toe and riverwards end is recommended • Likelihood of undercutting high
Hay Bale/Willow Revetments	Mesh-covered hay bales cabled together to form an inverted "T", anchored on lower bank. Upper bank planted with willow.	• Requires stone toe protection • Effective against toe scour, provides temporary mid-bank protection and eventual establishment of upper bank stabilization
Bendway Weirs	Low elevation entrenched stone structure oriented upstream.	• Length, spacing and radius of curvature critical • Diverts flowlines away from bankline towards centre of channel
Bioengineering Solutions Untested along Missouri River		
Straw-Coconut Blanket North American Green C125 or C125BN Maccaferri Inc	Fiber blanket designed to provide temporary bank protection while vegetation becomes established.	• Temporary solution – biodegradable after 2 to 3 years depending on product • Blankets can be placed over seedbeds or embedded with seedlings or stakes, using native vegetation, such as willow • Able to withstand high shear stresses (up to 2.35lbs/ft², or 112 Pa when vegetation established)
Turf Reinforcement Mat North American Green P300	Polypropylene fiber sandwiched between polypropylene netting.	• Permanent solution • Blankets can be placed over seedbeds • Able to withstand the same shear stresses as hard engineered solutions (up to 8lbs/ft², or 393 Pa when vegetation established)

Inappropriate bank protection schemes may have detrimental effects. Stabilization structures which use stone, such as riprap, significantly change the particle size of the

channel sediments. Different habitat conditions are, therefore, created, which may impact fish and wildlife (Weeks *et al.*, 2005). The impact of the potential reduction in the local sediment supply should also be taken into account. This is especially true if the reach requiring stabilization is close to collapse. A reduction in sediment supply could instigate bed erosion, creating further instability. In some cases, degradation may even be triggered in an aggrading reach (Biedenharn *et al.*, 2001).

The negative consequences of constructing an unsuccessful project are amply demonstrated by the Buford-Trenton Irrigation District bendway weir scheme discussed in Section 4.1.2. It is impossible to view one site in isolation as rivers are interconnected systems functioning as a complex whole (Phillips, 1992). Previous investigations of the FOUS study site have concluded that bendway weirs or tree revetment would provide a suitable solution to the problem. However, when designing a bank stabilization project, measures which result in a reduction in the channel width should be considered cautiously, since sand bar and island development could be adversely impacted (Biedenharn *et al.*, 2001). This is especially true for the study reach. The active channel to the south of the island is currently narrow. Thus, bendway weirs would almost entirely block this channel, diverting the flow towards the north side of the island. This is likely to instigate a major change in the position of the channel, which would have a dramatic impact on the planform of both the study reach and the reaches downstream. Tree revetment may prove effective, although care should be taken that scour does not occur behind the branches.

Although valuable to the NPS and FOUS, the land currently being eroded along the south bank of the Missouri is of little monetary value. Destruction of cottonwood and proximity to the nearby irrigation ditch, however, should not be discounted. It is the conclusion of this study, therefore, that implementation of stabilization measures would, at this time, not be cost-effective. However, monitoring of the rate and location of erosion should continue. If necessary, the construction of hay bale/willow revetments with stone toe protection would seem to be the most suitable form of stabilization. This type of project would have little visual impact and would hopefully enable vegetation, especially willow and cottonwood, to become established. The erosive effects of ice are likely to cause this type of soft bank protection to be less effective than in lower latitudes. However, as noted in Table 5.1, these revetments have been used with some success elsewhere along the Missouri River (Mellema, 1996).

Table 5.1 also summarizes other potentially suitable soft bank protection schemes. Implementation of bioengineering solutions, other than hay bale/willow revetments, may provide a sustainable, low-impact solution. North American Green manufacture several types of fiber blanket, which are suitable for placing over seedbeds, allowing stabilizing vegetation to become established. The high likelihood of ice erosion at the study site would require a solution able to withstand high shear stresses. North American Green's P300 Permanent Turf Reinforcement Mat is specifically designed to withstand high shear stresses, providing a bioengineering alternative to hard engineered bank protection, such as riprap. This solution is significantly cheaper and would have far less impact on local habitat than hard engineered solutions. This material is designed to withstand shear stresses of over 300 Pa (over 6 lbs/ft²), well over the maximum

critical shear stresses of 13.4 Pa (0.28 lbs/ft²) noted by Simon *et al.* (2002) along the Missouri River in Montana.

A1.4 Possible Sources of Funding

The USACE has a Section 14 program of funding bank stabilization projects each year (David LaGrone, pers. comm.). It would, therefore, be advisable to approach the Omaha District ACE with regard to this possibility. A sizeable quantity of stone was left over after the construction of the bendway weirs just downstream of FOUS, due to the change in their design. This could possibly be used to reduce the cost of any schemes. It is also possible that the cost could be shared equally with the Lower Yellowstone Irrigation District, as the irrigation ditch behind the eroding bank will be affected if bank retreat continues at the same rate.

A further possibility would be to develop a stabilization project which included the eroding reach close to Highway 58, which is currently managed by the state Department of Transport. This solution would be beneficial to several landowners as an holistic approach can be developed, with the aim of allowing Missouri to adjust naturally. This would ensure that the natural appearance of the study site was maintained, a factor important for interpreting the cultural landscape at FOUS.