HISTORICAL FLOODPLAIN SEDIMENTATION ALONG THE UPPER MISSISSIPPI RIVER, POOL 11

by

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Abstract

Many of the ecologically rich aquatic habitats created by the construction of locks and dams on the upper Mississippi River are now disappearing as a result of increased sedimentation. Sub-aqueous sediment cores were collected from two backwater lakes, one with a hydraulic connection to the main channel and the other with no low water connection to the main channel. Multiple lab analyses were combined with river stage data to provide a detailed history of sedimentation rates and processes in each lake. Estimated rates of sedimentation for the 1938-2003 post-lock and dam period range from 0.83-1.00 cm/yr in the backwater lakes. While the rates are much lower than rates found in most previous studies of upper Mississippi River backwaters, these rates of sedimentation are still high for the shallow backwaters and at least an order of magnitude above pre-Euro-American settlement rates. Analysis of a series of aerial photographs shows wide spread sediment deposition since dam operation, though there has been little terrestrial encroachment into the lakes. Large overbank floods contribute the majority of the sediment to the isolated backwater and a large percentage of sediment to the contiguous backwater. Terrestrial floodplain surveying and sediment sampling after the 2004 summer flood showed lower elevations generally had greater deposition and coarser sediments, though a large logjam also influenced flow direction and deposition patterns. Small floods on the upper Mississippi River are an important factor in floodplain evolution and have the ability to deliver sediment to backwaters on a near annual basis.

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Table of Contents

List of Figures

List of Tables

Chapter 1 - Introduction

The upper Mississippi River (UMR) is a complex river system that has undergone and continues to undergo significant changes in its morphology following settlement by European-Americans in the Midwest during the mid-19th Century. Land use/cover changes and floodplain modifications, coupled with a changing global climate, have altered the natural erosion and deposition processes of the UMR (Fremling and Claflin, 1984; Anfinson, 2003; West Consultants, 2000; Knox, 2001; Knox, 1987; Knox, 2003).

The UMR has become an important economic, environmental and recreational resource. Over the past two centuries the UMR has been modified by the U.S. Army Corps of Engineers to serve as a reliable transportation route for goods in and out of the Midwest through a series of navigation projects (Anfinson, 2003; USACE, 2002a). Environmentalists have continually sought to protect the great diversity of habitat, wildlife and natural beauty of the UMR Valley (Anfinson, 2003). Recreationists and tourists are attracted to that same diversity and annually contribute over a billion dollars to local economies along the UMR (Carlson *et al.,* 1995).

Many studies have cited sedimentation as a major threat to not only the biologically rich aquatic and floodplain habitat of the UMR, but also to the billion-dollar interests of recreation and shipping (Anfinson, 2003; McHenry *et al.*, 1984; Bhowmik and Adams, 1989; Eckblad, 1986; Fremling and Claflin, 1984; GREAT, 1980a; GREAT, 1980b). Several organizations, including the U.S. Fish and Wildlife Service and the U.S. Army Corps of Engineers, are interested in the floodplain areas of the UMR and continue to support research projects on floodplain sedimentation within the UMR valley (Rogala *et al.*, 2003; Rogala and Boma, 1996; Gaugush and Wilcox, 2002; West Consultants, 2000).

Although much research has been completed, there exists a need to develop further understanding of the spatially and temporally complex response of floodplain backwater lakes to the river's changing sediment loads, channel modifications and historic flood events to assist in the conservation planning of these vital areas. This thesis examines the sedimentological history of two backwater lakes on the floodplain of the upper Mississippi River, Pool 11, to improve understanding of the temporal and spatial variability of sedimentation processes within and between the backwaters. Backwater lakes are areas of open water located on the floodplain beyond the UMR's main and secondary channels (Wilcox, 1993). A small flood during June 2004 also provided the opportunity to examine processes and patterns of overbank flow, sediment transport, and sediment deposition within a localized terrestrial area of the alluvial floodplain.

The continued loss of backwater lakes as a result of sedimentation is a major geomorphic change occurring within Pool 11. The study area has been identified as a location that has experienced and will continue to experience the loss of vital backwaters (GREAT, 1980b; West Consultants, 2000). By the year 2050, a 20% reduction in isolated and contiguous backwaters is predicted for the portion of Pool 11 that includes the study area (West Consultants, 2000). Isolated backwaters are defined as having no hydraulic connection to the main channel of the UMR during normal river stages while contiguous backwaters are connected to the main channel flow (Wilcox, 1993). GREAT (1980b) reported that Pool 11 had already experienced a 200 hectare [495 acre] loss of off-channel habitat between 1956 and 1979 as a result of non-dredged spoil sedimentation.

Although there has been much research on backwater sedimentation within the UMR, many reasons still exist for studying these areas within the upper Mississippi River System.

The response of individual backwaters to sedimentation is complex and spatially variable (West Consultants, 2000), therefore the processes and changes occurring in one backwater are not always applicable to all other backwaters within the UMR. A greater understanding of the processes affecting a variety of different backwaters in different geographic locations will improve the understanding of the complex response following the closure of the locks and dams. Information on sediment transport to the backwater areas will also be beneficial to agencies attempting to reduce sediment delivery to the backwaters through structural means.

By estimating rates and variability of sedimentation for individual backwaters, it may be possible to determine how rapidly they are losing volume. Several previous studies have argued that through a gradual reduction in depth most backwaters will be converted into marshes or terrestrial land within 50 to 100 years (McHenry *et al.*, 1984; Eckblad *et al.*, 1977; Ritchie *et al.*, 1986). If this change occurs, it is thought the river will begin to function as an incised channel rather than a series of impounded lakes (Bhowmik *et al.*, 1986). Though this change may potentially benefit navigation interests and reduce dredging requirements by creating higher sediment transport capacities and a deeper thalweg, it would have detrimental impacts on the environment and flood stages.

Backwater areas are used by nearly all fish species at some point during their lives. The biotic quality of the UMR is dependent on the quality and accessibility of backwater habitats (GREAT, 1980b; Eckblad, 1986). An estimated three quarters of the migratory waterfowl in the U.S. depend on the backwaters of the UMR (GREAT, 1980a). In addition to habitat loss, floodwater storage capacity would decrease with the loss of backwaters, potentially leading to an increased stage/discharge relationship (Grubaugh and Anderson, 1989; Leopold, 1994). These concerns have made many researchers and planners interested in the changing dynamics of the UMR.

Results from this study will be useful in determining how sedimentation rates have varied over time at individual locations and how they vary between different types of backwaters (i.e. contiguous and isolated). The detailed analysis of sediment deposited in the backwaters will provide insight on the impact of large flood events on sedimentation at each location. This study will also provide valuable information on sediment transport across the floodplain during individual flood events. While smaller events like the June 2004 flood may not impact the entire floodplain, they still have the ability to deliver water and sediment to backwaters and play a role in floodplain evolution. With information from this thesis, planners will be better suited to predict how well different management strategies and projects have worked and how new strategies might impact these diverse areas. This thesis will also provide planners with new insights on the methodologies that may be useful when investigating backwater sedimentation rates.

Chapter 2 - Human modifications to the upper Mississippi River

The main navigation channel of the upper Mississippi River stretches for 850 river miles [1,367 km] from the confluence of the Ohio and Mississippi river at Cairo, Illinois upstream to Minneapolis, Minnesota (West Consultants, 2000) [fig. 1].

Navigation improvements on the upper Mississippi River (UMR) began as early as 1838 to improve steamboat passage on the river (Anfinson, 2003). The initial modifications included removal of rock from the Des Moines Rapids and the construction of a wing dam near St. Louis (Anfinson, 2003). By the mid 19th century the U.S. Army Corps of Engineers (USACE) was assigned the task of modifying the river channel and floodplain for the sake of improving navigation and increasing commerce. Despite the early work on the UMR, the river remained mostly natural until 1866 (Anfinson, 2003; USACE, 2002a).

Between 1866 and 1907 Congress authorized the USACE to establish and maintain a 1.22-meter [4-foot], a 1.37-meter [4.5-foot], and a 1.83-meter [6-foot] navigation channel for the purpose of navigation on the UMR (USACE, 2002a). Wing dams, backwater and side channel closing structures, revetments and dredging were all used to constrict flow within the main channel and maintain the required thalweg depths through scour (Fremling and Claflin, 1984; Anfinson, 2003). None of these projects succeeded in keeping the river open to navigation during extreme high and low river flows and they ultimately failed to provide competitive transportation of commodities. A shift to shipping by railroad and isolation of the Midwest by the Panama Canal further reduced river transport (Anfinson, 2003). Despite the Army Corps' monumental efforts in river training, by 1918 few commodities were transported on the river.

Figure 1. The upper Mississippi River System and its locks and dams from Cairo, Illinois, to Minneapolis-St. Paul, Minnesota.

As part of the Rivers and Harbors Act of 1927, Congress authorized the Corps of Engineers to construct a 2.74-meter [9-foot] channel through the use of a series of locks and dams (Anfinson, 2003; Fremling and Claflin, 1984; USACE, 2002a). Twenty-nine locks and dams were constructed on the UMR. The locks and dams effectively converted the river into a series of connected slackwater lakes and maintained a minimum 2.74-meter channel depth year round. The natural flow variability of the river has been permanently altered by the locks and dams. The USACE raises and lowers a series of roller dams to maintain the required flatpool elevation upstream of each lock and dam necessary for the 2.74-meter navigation channel. Large floods are relatively unaffected by the dams as they are passed through the raised rollers, but the river's average stage has increased considerably and the low discharge stages experienced prior to dam operation have been nearly eliminated [fig. 2] (West Consultants, 2000; Theiling, 1995).

The river no longer experiences the natural flood pulses that annually connected the river to its floodplain prior to lock and dam operation. The natural low stages of the summer and fall that allowed sediment to dry out and compact no longer occur. This process that is vital to many types of aquatic vegetation has been replaced by higher year-round water tables and inundated backwaters (Anfinson, 2003).

Many environmentalists feared the lock and dam system would be detrimental to the river's aquatic species while others believed it would increase floodplain diversity (Anfinson, 2003). During debates on the construction of the locks and dams, accelerated siltation was recognized as a major concern (Anfinson, 2003). Siltation had been a problem within the UMR since early 1900's (Anfinson, 2003). The lock and dam system initially increased the number and size of aquatic areas by inundating large portions of the floodplain, therefore initially increasing the biodiversity of the river system (Fremling and Claflin, 1984; Anfinson, 2003; Olson and Meyer, 1976). It is the same impoundment of water that has reduced the river's sediment transport capacity and is causing the deposition of sediments in expanded and recently created backwaters (McHenry *et al.*, 1984).

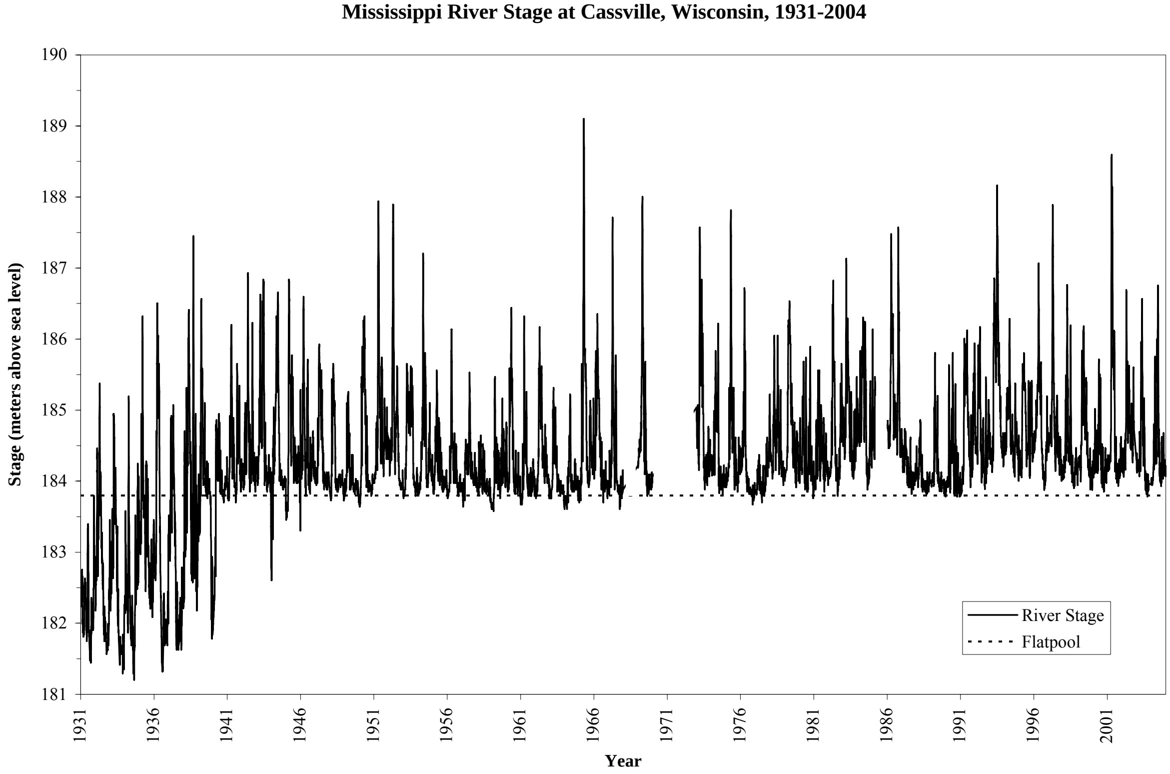


Figure. 2. River stage at Cassville, Wisconsin, showing the reduction in natural stage variability following the construction of Lock and Dam 11 in 1937. Gaps in graph represent data currently unavailable. (Data Source: U.S. Army Corps of Engineers).

Slackwater conditions upstream of the locks and dams and in the backwaters combined with higher tributary stream base levels led to rapid sedimentation. Coarse sediments delivered by tributary streams are no long transported downstream by the Mississippi River during low and intermediate flows and are instead deposited at the mouth of the tributary streams in the UMR channel and backwaters (Nakato, 1981a; Knox and Faulkner, 1994).

As previously discussed, the loss of the backwater areas by the gradual filling with sediments will continue to reduce the biological diversity of the river and its floodplain. Areas that were once biologically rich habitats may return to marsh or terrestrial forest habitat (Fremling and Claflin, 1984; Bhowmik and Adams, 1989; Bhowmik *et al*., 1986; McHenry *et al*., 1984). Sedimentation is also a threat to the long-term biological diversity of backwaters and terrestrial floodplain areas because sediments are often a potential source of pollution (Great, 1980b). Pollutants may be stored on the floodplain for years and create future environmental problems.

Several efforts have been made to reduce the impact of sedimentation within UMR backwaters. Congress declared the UMR a nationally significant ecosystem and navigation system and required agencies to regulate the river for both environmental sustainability and navigation needs (Anfinson, 2003). Recently, many habitat rehabilitation projects have been constructed by USACE in conjunction with other government agencies (Janvrin, 1998; Theiling, 1995; USACE, 1996), but these localized projects have only focused on small-scale reduction of sedimentation within side channels and backwaters (Theiling, 1995). Theiling (1995) proposed system-wide pool drawdowns to mimic the low water stages and flood pulses that existed prior to lock and dam closure. It is thought these drawdowns will aid in backwater sediment stabilization, consolidation and compaction. One to two foot drawdowns have been successfully implemented in Pools 24-25 since 1994 (USACE, 2002a) and are currently being tested in several pools operated by the U.S. Army Corps of Engineers St. Paul District (USACE-MVP, 2004).

Chapter 3 - Literature Review

3.1. Sedimentation Trends in the Upper Mississippi River Valley

Sedimentation is a natural process and the UMR floodplain has been aggrading for thousands of years. Knox (2001) estimated a floodplain aggradation rate of approximately 0.06 cm/year at Island 146 near Lansing, Iowa, over the past 6,000 years. Benedetti (2003) estimated a mean floodplain aggradation rate of 0.014 cm/year in Pool 10 over the past 2,500 years.

Natural rates of sedimentation have been accelerated by European-American settlement in the Midwest beginning in the mid-18th Century. Logging, mining and agricultural practices within the upper Mississippi River valleys have decreased the natural vegetation cover and increased erosion rates through accelerated overland runoff. These land use changes have introduced large volumes of sediment to tributary streams and the Mississippi River (Knox, 2001; Knox and Daniels, 2002; Knox, 1987). Approximately 3.5 meters of overbank sediment has been deposited on the lower reaches of the Little Platte River floodplain after the settlement and widespread agriculture in the watershed during the 1820's (Knox, 2001). Aggradation rates at Island 146 near Lansing increased more than an order of magnitude to a post-settlement rate of 1-2 cm/year (Knox, 2001). Floodplain aggradation rates at the sites studied by Benedetti (2003) increased nearly two orders of magnitude to a mean of approximately 1 cm/year after 1954 in Pool 10.

Although post-settlement rates of sedimentation remain higher than the long-term rates, sedimentation appears to have decreased beginning in the 1950's and 1960's from improved farming and land conservation practices (McHenry *et al.*, 1984; Knox, 1987; Anfinson, 2003; West Consultants, 2000; Bhowmik and Adams, 1989; Benedetti, 2003).

Pannel (1999) found that the suspended sediment concentration measured downstream of Lock and Dam 11 significantly decreased during 1943-1996 from about 1,000 ppm to 200 ppm. Land management improvements may not have been the only reason behind decreasing sedimentation rates. Decreasing backwater and floodplain depths may also lead to slower sedimentation rates. As lake bottom elevations increase, a smaller mass of sediment is suspended in a column of water per unit area of the floodplain and inundation times may be decreased (Walling and He, 1997; Steffeck *et al*., 1980; Asselman and Middelkoop, 1995). Transport capacity of the main channel also increases as floodplain storage is reduced, further reducing floodplain sedimentation rates (Steffeck *et al*., 1980; Bhowmik and Adams, 1989; Bhowmik *et al*., 1986).

Improved land management practices have reduced agricultural erosion and sediment supply, yet ironically the cleaner tributary water has remobilized alluvium stored in UMR tributary valleys (Knox, 2001; Knox and Faulkner 1994). Gullying in tributary basins has maintained high sediment transport delivery to the UMR. Isolation of tributary streams from their former floodplains has decreased overbank sedimentation in the tributary valleys and increased the streams' ability to convey high sediment loads to the Mississippi River (Faulkner and McIntyre, 1996; Knox, 1987).

The continuation of large floods on the UMR may also maintain high sedimentation rates despite improvements in land management. Benedetti (2003) estimated 29 floods accounted for 37% of the suspended sediment load of the UMR measured at McGregor, Iowa, from 1976-2002. The majority of overbank sedimentation since the closure of the locks and dams appears to result from a small number of large floods on the UMR (Benedetti, 2003; Theis and Knox, 2003; Knox, 2001). The UMR has experienced episodes of large magnitude, frequent floods at the onset of warming periods over the past 7,000 years (Knox, 2003). Global warming may be a driving force behind the numerous recent large floods on the upper Mississippi River System (Knox, 2003). Knapp (1994) also found climate changes during the 20th Century in the form of post-1965 increases in average annual precipitation. This increased precipitation, rather than anthropogenic changes in the upper Mississippi River System, may be a principal factor behind increasing flood discharges. The combination of tributary sediment remobilization and high tributary conveyance capacities with large floods on the UMR driven by a changing climate may cause continued high sediment loads and siltation of backwaters, despite the improvements in land management practices.

3.2. Backwater Sedimentation within the Upper Mississippi River Floodplain

Many previous studies have attempted to assess rates of sedimentation within backwater lakes on the upper Mississippi River floodplain [table 1]. The geographic location of these studies, the methods used, and the study period often differ, and varying results therefore exist between the study areas.

Bathymetry data, often in association with other methods, have been used in many studies of backwater sedimentation within the UMR. Eckblad *et al.* (1977) estimated sedimentation rates in Big Lake, a large contiguous backwater in Pool 9, using 1896 survey maps and bathymetry data collected in 1973. Twelve sediment cores were also taken across four of the survey transects to be analyzed for ^{137}Cs. The backwater had a maximum depth of two meters and a mean depth of only 0.89 meters. Where sloughs entered contiguous backwater areas, grain sizes were larger. Data from the 1896 and 1973 surveys gave an average sedimentation rate of 2.11 cm/yr while the ^{137}Cs analyses gave a lower rate of 1.69 cm/yr from 1964-1974.

Source	Location	Backwater Type	Method	Time Period	Sedimentation rate (cm/yr)
McHenry *et al*. (1976)	Pool 10	Unknown	^{137}Cs	1955-1975	3.5
				1963-1975	4.2
Eckblad *et al*. (1977)	Pool 9	Contiguous	Bathymetry	1896-1977	2.11
			^{137}Cs	1964-1974	1.69
Claflin (1977)	Pool 7	Impounded	Bathymetry	1937-1976	1.64
Nakato (1981b)	Pool 11	Unknown	Bathymetry	1938-1951	0.67
	P11- RM 610	Contiguous	Bathymetry	1938-1951	-0.45
	P11- RM 600	Contiguous	Bathymetry	1938-1951	3.9
	P11- RM 598	Impounded	Bathymetry	1938-1951	1.13
McHenry *et al*. (1984)	Pool 7	Impounded	^{137}Cs	1954-1977	1.66
	Pool 14	Contiguous	^{137}Cs	1954-1964	3.76
				1964-1980	1.17
	Pools 4-10	Unknown	^{137}Cs	1954-1964	3.4
				1964-1975	1.8
Korschgen *et al*. (1987)	Pool 7	Impounded	Bathymetry	1937-1983	0.2
Knox and Faulkner (1994)	Pool 4	Tributary Impounded	Bathymetry	1935-1945	3.3
				1935-1992	2.2
			^{137}Cs	1945-1954	1.4
				1954-1965	1.3
				1965-1992	2.4
Rogala and Boma (1996)	Pool 4	Isolated/Contiguous	Bathymetry	1989-1996	0.29
	Pool 8	Isolated/Contiguous	Bathymetry	1989-1996	0.12
	Pool 13	Isolated/Contiguous	Bathymetry	1989-1996	0.8
Rogala *et al*. (1997)	Pool 8	Contiguous	Pre-Impoundment Soil Identification	1939-1997	0.46
USACE (2002)	Pool 11 – Bertom Lake	Contiguous	Unknown	1938-1988	1.78
	McCartney & Bertom Lakes	Contiguous	Unknown	1938-1988	0.99
West Consultants (2000)	Pool 11 RM 584-597	Impounded	Bathymetry	1938-1995	0.64
				1938-1951	1.56
				1951-1995	0.34
Rogala *et al*. (2003)	Pool 4	Isolated/Contiguous	Bathymetry	1997-2001	-0.08
	Pool 8	Isolated/Contiguous	Bathymetry	1997-2001	0.21
	Pool 13	Isolated/Contiguous	Bathymetry	1997-2001	0.47
Theis and Knox (2003)	Pool 10	Isolated	Particle Size Analysis (individual cores)	1938-2001	0.63-0.73
				2001 Flood	10-47

Table 1. Recent rates of sedimentation in backwater areas of the upper Mississippi River.

Korschgen *et al*. (1987) estimated sedimentation rates in Lake Onalaska, an 1,100 hectare [2,800 acre] impounded backwater in Pool 7. Digital elevation surface grids were created for the lake bottom based on 1933 pre-lock and dam survey maps and 1973 bathymetry surveys. Lake Onalaska only experienced an average of 0.2 cm/yr of sedimentation. Results show that within Lake Onalaska locations near stronger currents experienced scouring while isolated areas accumulated sediment.

Results from Korschgen *et al*. (1987) are much lower than those reported by McHenry *et al*. (1984) and Claflin (1977) in their study of Lake Onalaska. McHenry *et al*. (1984) estimated an average sedimentation rate of 1.66 cm/yr from 1954-1977 based on ^{137}Cs dating of 14 sediment cores. Claflin (1977) estimated a nearly identical average sedimentation rate of 1.64 cm/yr from 1937-1976 using similar techniques as Korschgen *et al*. (1987). Results from McHenry *et al*. (1984) are likely higher because samples were taken only in areas of known sediment accumulation. It is unclear why Claflin (1977) had such higher rates of sedimentation than Korschgen *et al*. (1987) when similar techniques were used in both studies.

Knox and Faulkner (1994) and Faulkner and McIntyre (1996) estimated sedimentation in Riecks Lake, Pool 4, using a combination of bathymetry data and cross-section surveys. Riecks Lake formed at the mouth of the Buffalo River after impoundment of the UMR in 1935. Flow from Buffalo River has been slowed by Riecks Lake and accelerated sedimentation has occurred at the tributary’s mouth after the construction of Lock and Dam 4. Despite improvements in land use within the watershed, high rates of sedimentation in Riecks Lake have continued. Gullying within the watershed has increased

Buffalo River's floodwater and sediment conveyance capacity and decreased overbank floodplain sedimentation within the Buffalo River Watershed.

Nakato (1981b) estimated rates of sedimentation within Pool 11 by comparing bed elevation changes between 1938 and 1951 surveys. The surveys were conducted at each river mile in Pool 11, and an average sedimentation rate of 0.67 cm/yr was found. The surveys indicated that the upper third of the pool experienced net erosion, the middle third experienced erosion and deposition and the lower third experienced net deposition. It is apparent in the cross-sections that deeper zones within the backwaters in the middle and lower pool were filling more rapidly than shallower areas, creating a homogenous bed topography. Nakato (1981b) only compared areas at or below the flat-pool elevation when estimating sedimentation rates and also noted large variability in sedimentation between cross-sections and within a single cross-section. Unfortunately, most of these surveys have not been continued for areas outside of the main channel since 1951, preventing further analysis of post-impoundment trends.

West Consultants (2000) used a subset of the survey cross-sections presented by Nakato (1981b) to determine rates of sedimentation specifically for the impounded stretch of lower Pool 11. An average sedimentation rate of 1.56 cm/yr for 1938-1951 is higher than what Nakato (1981b) found for Pool 11 because the study only focused on the rapidly aggrading impounded backwater. A resurvey of the cross-sections in 1995 indicates the sedimentation rates dropped significantly to 0.34 cm/yr. It is thought that as Pool 11's backwater areas fill in, greater amounts of sediment will be transported to pools downstream of Lock and Dam 11 (West Consultants, 2000). This change in Pool 11's sediment balance may increase sedimentation problems in the downstream reaches of the UMR.

Concerns about the shallow water and rapid loss of the diverse wildlife habitat in Pool 11 have caused the U.S. Army Corps of Engineers, in cooperation with several other government agencies, to construct a habitat rehabilitation and enhancement project (HREP) in the contiguous backwaters from river miles 599.0-602.8. A partial closing structure was constructed in a channel entering Bertom Lake in an attempt to reduce the delivery of bedload sediment to the project area. Dredging to provide deeper, better connected habitat and the construction of an island to reduce sediment resuspension and turbidity by reducing the lake's fetch were also undertaken in 1992 (Janvrin, 1998; USACE, 1996). The total cost of this single localized project was $2,244,278 (USACE, 1996).

The fish population in the lakes took six years to respond to the increased water depths (Janvrin, 1998), but continued sedimentation threatens the longevity of the project. Sedimentation rates in the dredge cuts were nearly four times greater than expected and may reduce the project's predicted 50 year life to as short as 25 years (USACE, 2002b). Overall sedimentation rates for the entire HREP study area before project construction were 0.99 cm/yr, while Bertom Lake experienced a higher rate of 1.77 cm/yr from 1938-1988. Field observations show the partial closing structure has had limited success in slowing the growth of a delta into Bertom Lake. The 1993 and 2001 floods contributed large volumes of sediment to the project area (USACE, 2002b).

Many studies used lake coring and ^{137}Cs analysis to estimate backwater sedimentation rates. Unlike the projects discussed above, several of the studies have been vague about where their cores were extracted within UMR backwaters (McHenry *et al.*, 1976; Ritchie *et al.,* 1986; Ritchie and McHenry, 1985; McHenry *et al.*, 1984). Some of these studies in Pools 4-10 only extracted cores from impounded areas directly upstream of the lock and dam structures (Ritchie *et al*., 1986; Ritchie and McHenry, 1985). Maps locating the sites are not given, and there is no specification of how rates vary across the backwaters. Results are lumped into one backwater accumulation rate for each pool leaving unreported the variability within pools and within individual backwaters. Mean rates of sedimentation ranged from approximately 1-4 cm/yr depending upon the pool and time period (McHenry *et al*., 1984; Ritchie *et al*., 1986). These types of results are difficult to use for assessing long-term sedimentation trends because of poorly defined site identifications. The samples were also only collected in areas of net fine sediment accumulation and a low sampling resolution for ^{137}Cs dating was used. The results show a trend towards decreasing rates of sedimentation at nearly all sites in Pools 4-10 and 14 after 1964 (McHenry *et al*., 1984; Ritchie and McHenry, 1985; McHenry *et al*., 1976).

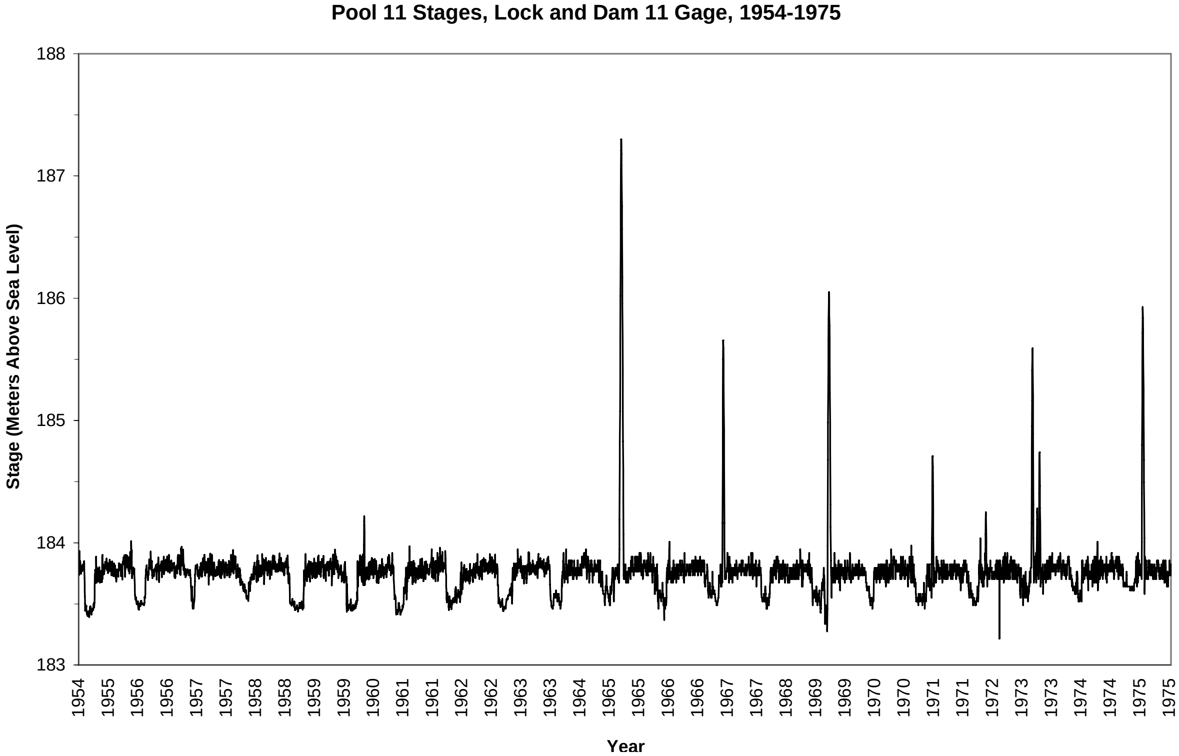


Figure 3. Pool stages measured at Lock and Dam 11 from 1954-1975. (Data Source: U.S. Army Corps of Engineers)

This post 1963 decrease in sedimentation in studies using ^{137}Cs has been attributed to improvements in land use management, however the decrease may also be associated with the flushing out of fine sediment from the backwaters during several major floods from 1965-1975. Four of Pool 11's ten largest floods recorded at Lock and Dam 11 occurred during the ten years from 1965-1975, including the UMR's largest flood on record in 1965. The period of 1954-1964 had no major floods and may have been a period of net fine sediment accumulation in contiguous and impounded backwaters [fig. 3]. No discussion of how floods might have impacted sedimentation rates estimated from ^{137}Cs analysis was provided by these previous studies using ^{137}Cs.

Several recent studies have better specified the spatial variation that occurs when sediment settles out of suspension in backwater lakes (Theis and Knox, 2003; Rogala and Boma, 1996; Rogala *et al*., 2003; Rogala *et al*., 1997). Post-impoundment rates of sedimentation in Pool 8 were 0.29 cm/yr for small high-connectivity backwaters (<50 ha with more than 2 inlets), 0.43 cm/yr for small low-connectivity backwater lakes (<50 ha with 1 or 2 inlets), and 0.57 cm/yr for large backwaters (>50 ha) (Rogala *et al*., 1997). High spatial and temporal variability in deposition, stability and erosion within individual backwaters was found in Pools 4, 8, and 12 (Rogala and Boma, 1996; Rogala *et al*., 2003). This suggests it is not possible to extrapolate results from a few cores to an entire backwater or pool as some of the previously discussed studies did.

The recent studies have found much lower rates of average sedimentation in aquatic areas than prior studies, ranging from -0.08 cm/yr to 0.84 cm/yr (Theis and Knox, 2004; Rogala and Boma, 1996; Rogala *et al*., 2003; Rogala *et al*., 1997). Negative rates of sedimentation at some locations resulted from scouring and bank erosion within contiguous backwater areas, especially during high discharges when deeper, higher velocity flows have greater shear stress (Rogala *et al*., 2003). A comparison of surficial sediment grain sizes and cross-sections taken in lower Pool 11 before and after the 1993 flood indicate a flushing out of fine sediments from impounded backwaters and a scouring of main and secondary channels during the 1993 flood (Moody 1997a; Moody 1997b). These findings may substantiate why many of the studies using ^{137}Cs found lower rates of sedimentation during the period of increased large magnitude flooding after 1964, and higher rates of sedimentation during the period of small, infrequent floods from 1955-1964.

Theis and Knox (2004) attempted to control for the possibility of erosion by faster currents experienced in some contiguous backwaters by focusing on four isolated backwaters within Pool 10. The isolated backwaters do not typically have sediment supplied to them during lower stages. By using particle size analysis with a variety of other methods, it was possible to identify specific episodes of sediment deposition in the backwater lakes. Theis and Knox (2003) found that the isolated backwaters experienced the majority of sedimentation during major flood events, not during periods of small, infrequent floods.

No studies have explicitly compared sedimentation rates and processes of an isolated backwater to an adjacent contiguous backwater. Theis and Knox (2003) compared isolated backwaters and many of the other previous studies only investigated impounded areas and large contiguous backwaters. Rogala and Boma (1996, 2003) had a few isolated backwaters in their studies, but no direct comparisons were made between the isolated and contiguous backwaters. It is thought that sedimentation in isolated backwaters will be much more episodic than in contiguous backwaters. Contiguous backwaters receive flow and sediment throughout most of any given year and during most years, whereas isolated backwater typically only receive river flow and sediment during overbank floods. A detailed study of adjacent contiguous and isolated backwaters would provide valuable insight into the spatial and temporal variation in sedimentation at the two types of sites.

3.3. Limitations of Previous Studies

The methods used to estimate sedimentation within backwaters are numerous and provide varying results. Bathymetry data often provide a longer term average if pre-lock and dam data are used, however it is often difficult to align pre-lock and dam survey data with recent survey data. Detailed pre-lock and dam survey data are also not available for all areas within the UMR. Rogala and Boma (1996) and Rogala and Boma (2003) established survey lines that could be found and accurately resurveyed yearly. The reliability of the bathymetry data improved, however results only encompass a few years of sedimentation and the annual resurveying of each site is time intensive. The surveys also provide no information on the type of sediment deposited.

^{137}Cs dating of sediments has been widely used. Multiple dates are obtainable and changes in sedimentation rates over time may be observed. ^{137}Cs is expensive and, historically, large samples were needed for accurate results. Most studies sampled at ten centimeter intervals and large errors may have been introduced when applying dates and determining sedimentation rates for a core. When using such a low sampling resolution a range in rates should be given, not just the maximum, minimum or mean. ^{137}Cs also has typically only been used in areas accumulating fine grained sediments, and it does not provide rates of sedimentation for time periods earlier than 1954.

Rogala et. al. (1997) and Ritchie and McHenry (1985) both used methods that attempted to identify the depth to the pre-impoundment surface. This surface may be identified by a buried soil, buried organic matter, a sharp change in bulk density or a sharp change in grain size. This method is highly subjective and relies on the fact that changes in the above characteristics are evidence of the pre/post-lock and dam sediment boundary. A sharp change in grain size may not strictly indicate the pre-impoundment surface. An abrupt change to a thick layer of medium to fine sand is often found beneath the more recent silty sediments (Benedetti, 2000). The sandy layer may be the former channel bed or point bar deposits, not strictly the pre-impoundment surface.

The above methods do not provide much insight into how the sediments were deposited, when specifically they were deposited, or from where the sediments may have been transported. They also do not take into account the compaction of sediments over time through burial. Theis and Knox (2003) is the only study that specifically looked at how backwater sedimentation has varied over longer time scales through the use of grain size analysis, carbonate analysis, ^{137}Cs dating, bulk density and organic carbon analysis. Knox (2001), Knox and Daniels (2002), and Benedetti (2003) are some of the few studies that have used a variety of methods including ^{137}Cs dating, grain size analysis and organic carbon analysis in conjunction with river stage data to estimate historical rates and variability on terrestrial floodplain areas. The combined use of these various methods is necessary to understand the processes behind backwater sedimentation at a particular location. Knowing only rates of sedimentation is not sufficient in the study of backwater areas. Only an understanding of the variable rates and processes through time will help planners choose the best approach in reducing the impact of backwater sedimentation.

3.4. Terrestrial Sedimentation within the UMR

Few studies on the UMR have investigated how floodplain topography and large woody debris (LWD) affect sedimentation on terrestrial areas of the floodplain. Microtopography, debris dams and floodplain vegetation potentially play in important role in sediment storage, erosion and transportation across the floodplain.

Benedetti (2003) sampled flood deposits at several sites affected by overbank sedimentation after the 1993, 1997, and 2001 floods. Overbank deposits in Pool 10 were described as generally silty mixed with fine (125-250 μm) and very fine (63-125 μm) sand layers deposited during floods. A small number of overbank floods accounted for the majority of floodplain deposition, despite near annual floodplain inundation. Benedetti (2003) also found the timing of the flood peak, suspended sediment concentration during the flood peak and flood duration are important factors influencing the amount of deposition that occurs, not just the magnitude of the flood.

Deposition and erosion patterns during the 1993 summer flood near Canton, Missouri varied with flow patterns and local topography (Gomez *et al*., 1997; Gomez *et al*., 1995). The depth of the deposited sediment was found to decrease with distance from the main channel. Depressions on the floodplain concentrated flood waters and acted as settling basins, and therefore had thicker flood deposits. Gomez *et al*. (1995) found that although the 1993 flood had a recurrence interval of greater than 100 years near Canton, little sediment deposition occurred on the floodplain. Similar to Benedetti (2003), Gomez *et al*. (1995) claim that event sequencing and the timing of the flood during the summer of 1993 reduced the flood’s suspended sediment concentration and therefore reduced its geomorphic impact.

Microtopography is a major control on floodplain sedimentation processes and patterns (Walling and He, 1997; Walling and He, 1998; Asselman and Middelkoop, 1995; Middelkoop and Asselman, 1998). Middelkoop and Asselman (1998) estimated that local floodplain depressions had 50-100% more deposition than areas higher on the floodplain in their study of the Waal and Meuse rivers in the Netherlands. If they are not isolated from the main channel, distributary or residual floodplain channels may also experience high rates of sedimentation by receiving flow and sediment input during lower river stages. During larger magnitude floods the accumulated sediment may be removed by faster currents, resulting in increased channel bank deposition (Asselman and Middelkoop, 1995).

The presence of large woody debris (LWD) also significantly impacts the patterns of sedimentation on floodplains, as shown in the study of a low order stream in England (Jeffries *et al*. 2003). LWD on the floodplain can cause high variability in sediment deposition by creating variability in the overbank flow pathways. Jeffries *et al*. (2003) reported that the thickest depositional units were found in the transition zone between flowing and ponded water, such as around a LWD dam. Floodplain channels concentrate flood waters and can transfer sediment across the floodplain.

Several methods have been used to document floodplain sedimentation patterns, processes and evolution. Many studies have focused on individual flood events in their discussion of floodplain deposition. Gomez *et al*. (1997) estimated floodplain sedimentation patterns and mechanisms after a single large flood by estimating the depth of sediment deposited inside a breached levee district and by estimating suspended sediment concentrations through analysis of Landsat 5 Thematic Mapper images taken during the 1993 flood. Sediment traps made of artificial grass have been used to investigate floodplain sedimentation variability during a single flood event (Middelkoop and Asselman, 1998; Jeffries *et al*., 2003).

Many methods for medium to longer scale records of floodplain development have also been used. Benedetti (2003) explored the controls on floodplain sedimentation of the UMR through the use of buried soils, ^{137}Cs, and post-flood surveys of sediment deposition. ^{137}Cs and ^{210}Pb have been used to estimate spatial patterns of sedimentation over longer time frames and multiple events (Walling and He, 1997; Walling and He1998). He and Walling (1998) explored lateral and longitudinal trends in the grain size variability of floodplain deposits by comparing the grain size of surface deposits. Temporal variability of large floods and overbank deposition in the upper Mississippi River Valley have been studied extensively through the use of grain size analysis, heavy metals, organic carbon analysis, and radiocarbon dating (Knox and Daniels, 2002; Knox, 2001; Knox, 1987).

More work is needed to understand the influence of LWD and microtopography on sedimentation patterns and processes within the UMR. Most areas of the floodplain are flooded on a near annual basis. An increased understanding in the influences of microtopography and LWD will advance the knowledge of floodplain evolution in the upper Mississippi River System. Because LWD and microtopography can be variable from one flood event to the next, post-flood surveying of sediment deposits is the most valuable way to understand an individual flood’s influence on sedimentation patterns and processes. Information on the flow of water and sediment across the UMR floodplain will also provide valuable insights into sediment transport to backwaters and the ability of channel structures to slow backwater sedimentation as has been attempted in Pool 11 by the USACE.

Chapter 4 – Study Area and Methodology

4.1. Study Area

This research project examines the temporal and spatial variability of floodplain sedimentation within the upper Mississippi River (UMR). The study area is located within Pool 11 of the UMR, southeast of Cassville, Wisconsin on the left bank floodplain between river miles 603 and 604 [kilometers 970 and 972] (T. 3N, R. 5W, 4th P.M., Sec. 34 and 35) [Fig. 4]. Sedimentation patterns and processes at two backwater lakes and one terrestrial floodplain site were examined within the study area during the course of 2004 [fig. 6].

The operation of Lock and Dam 11 at Dubuque, Iowa, 583 river miles [938 km] above the confluence of the Ohio and Mississippi Rivers, began in 1937 and Pool 11 formed upstream of the structure. Pool 11 stretches for 32.1 miles [51 km] from Dubuque, Iowa to Guttenburg, Iowa and has a drainage area of 212,638 km^2 [82,100 mi^2] (West Consultants, 2000). The Mississippi River at Pool 11 flows through a bedrock gorge of erosionally resistant limestone and dolomite (West Consultants, 2000). Lock and Dam 11 has had its largest effect directly upstream of the structure where large impounded lakes formed while the upper reaches of Pool 11 has retained a more natural island braided morphology. The study area is located in the transition zone between the island braided morphology and the impounded lake morphology.

Many steep tributaries drain into Pool 11 from the surrounding hills of the Wisconsin Driftless Area and the glaciated Paleozoic dissected uplands of northeast Iowa (Knox, 1987; Fremling and Claflin, 1984). Thick deposits of easily erodable loess cover the Ordovician dolomite and limestone of the Driftless Area and adjacent areas in northeast Iowa (Leigh and

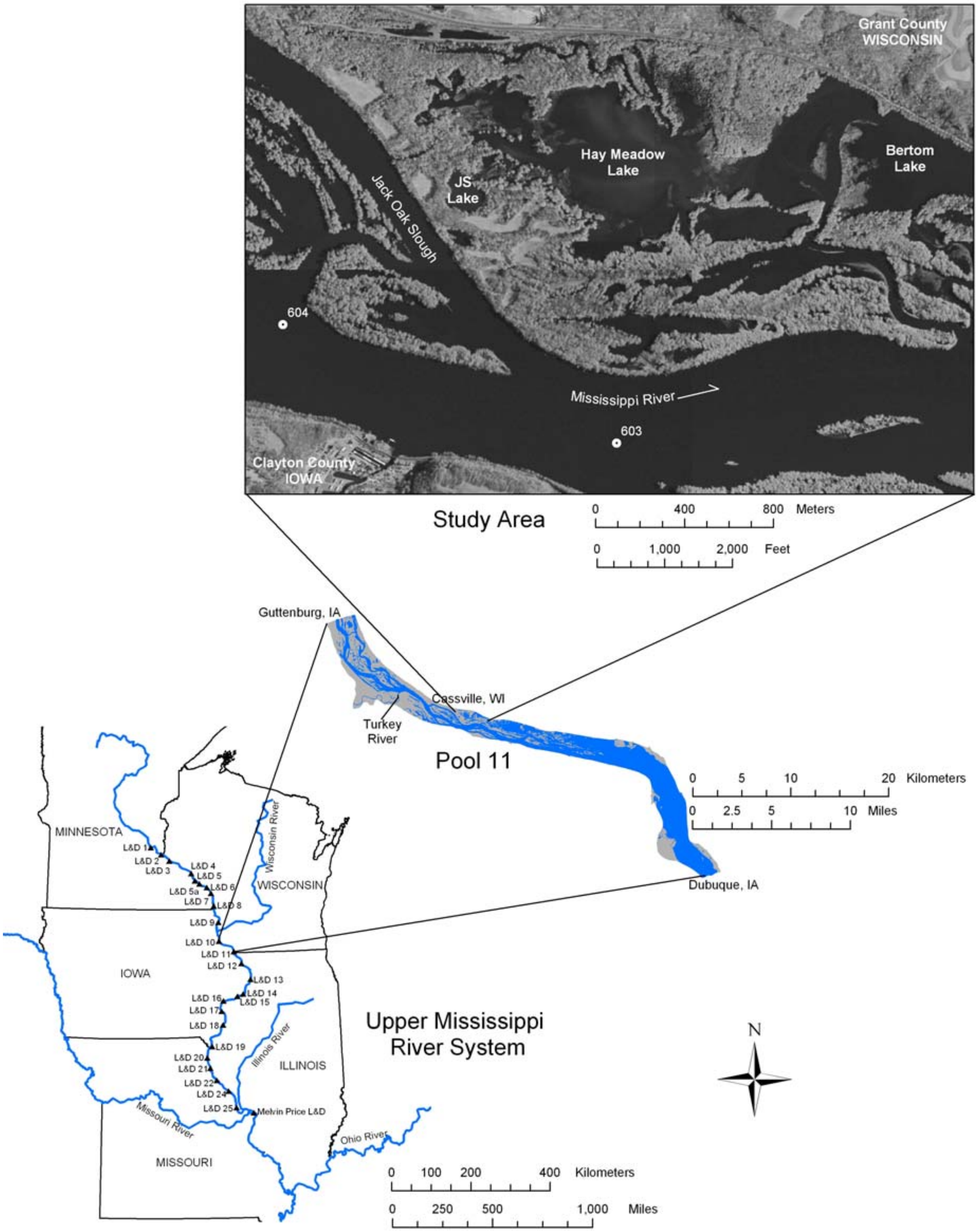


Figure 4. Location of the study area within the Upper Mississippi River System, Pool 11.

Knox, 1994; Knox, 1987). This highly dissected and intensely cultivated landscape supplies high levels of suspended sediment to Pool 11 (West Consultants, 2000). As a result of the Mississippi River's reduced sediment transport capacity following the closure of Lock and Dam 11, the river is incapable of transporting all of the delivered sediment out of Pool 11 (West Consultants, 2000; Nakato, 1981a).

The Turkey River, five river miles [8 km] upstream of the study site, has one of the highest tributary sediment loads in the UMR and is one of the largest contributors of sediment to Pool 11. Annually, an estimated 1,045,484 metric tons [1,152,449 tons] of suspended load and 420,422 metric tons [463,436 tons] of bedload is delivered directly to Pool 11's thalweg by the Turkey River (West Consultants, 2000). An estimated 2,314,783 metric tons [2,551,612 tons] of sediment annually passes through Lock and Dam 10, 12.8 river miles [20.6 km] upstream of the study sites (West Consultants, 2000). Sediment from the Turkey River and the sediment passed through Lock and Dam 10 likely provide the majority of the sediment entering the study site during moderate to high river stages.

The two lakes studied include an isolated backwater lake and a contiguous backwater lake [fig. 6]. According to Wilcox's (1993) classification, isolated backwaters have no low water surface flow connection to the main channel of the Mississippi River, while contiguous channels are connected by surface flow to the main channel. The isolated backwater, referred to as JS Lake, has an area of approximately 2.0 hectares [~5 acres] and the contiguous backwater, Hay Meadow Lake, has an area of approximately 40.5 hectares [~100 acres].

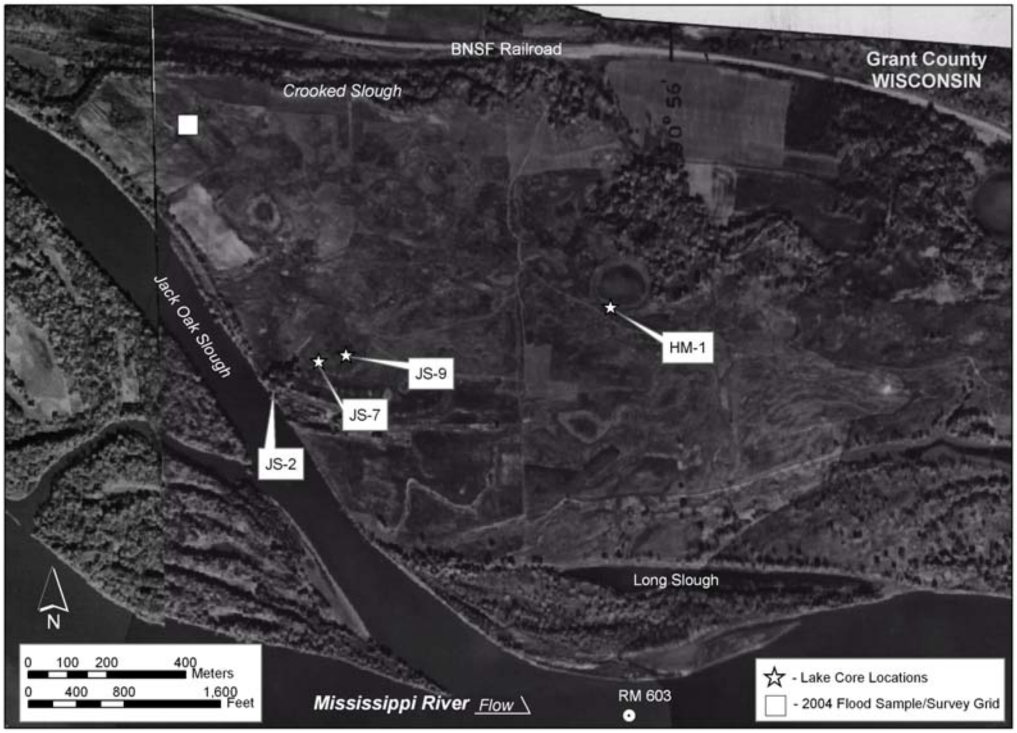


Figure 5. 1930/31 Brown's Survey aerial photograph of the study area showing locations of lake cores and 2004 flood deposit sampling/survey grid.

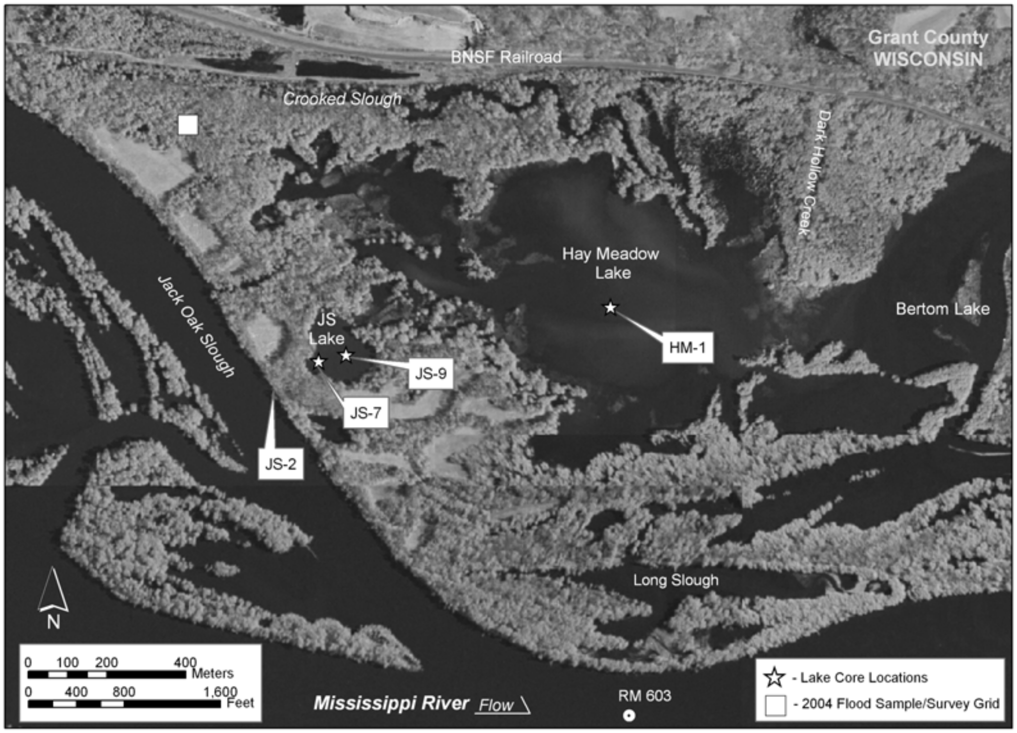


Figure 6. 2002 aerial photograph of the study area showing locations of lake cores and the 2004 flood deposit sampling/survey grid. (Image source: Iowa Geographic Image Map Server)

Many distributary channels connect Jack Oak Slough, a large secondary channel, and the main channel of the UMR to Hay Meadow Lake during moderate to low discharges. JS Lake is isolated from flow throughout most of the year. Water may enter JS Lake during moderate stages from Hay Meadow Lake or through low areas and breaks in the natural levee bordering Jack Oak Slough. JS Lake is protected from direct overbank flows below approximately 187.4 meters above sea level [618.4 feet asl] by a natural levee immediately west of the JS Lake study site. No tributary streams flow directly into the study area. Mill Branch Creek, a minor tributary stream, flows into Jack Oak Slough directly north of the study area and the mouth of the minor tributary Dark Hollow Creek is located immediately south of the study area between Hay Meadow and Bertom Lakes. It is not thought that these streams contribute high sediment loads to the study site (USACE, 1989), though a fan built by Dark Hollow Creek does likely affect flow between Hay Meadow and Bertom Lakes.

These two backwaters are ideal sites to study. They are accessible by road. They are located only 3.3 river miles [5.3 km] downstream of the Cassville stream gage and 20 river miles [32.2 km] upstream of the Lock and Dam 11 stream gage. The Cassville gage provides a nearly continuous record of river stage beginning in 1930 and the Lock and Dam 11 gage provides a nearly continuous record of stage and discharge beginning in 1935. The lakes provide the opportunity to study differences in sedimentation between two adjacent, yet, hydraulically different backwaters. The study area is in the vicinity of Mississippi River sedimentation research completed by Professor Jim Knox of the University of Wisconsin, Department of Geography. The sedimentary record at the backwater locations has not been disturbed by dredging or dredged spoil placement (West Consultants, 2000). The sites were also chosen due to the large effect the construction of Lock and Dam 11 and the impoundment of the UMR had on the study area [figs. 5 & 6].

Prior to the closure of Lock and Dam 11, the study area consisted mainly of agricultural fields, meadows and small tracts of forests. JS Lake was a small floodplain depression and Hay Meadow Lake was a small isolated floodplain lake prior to lock and dam operation. Currently the study area consists of floodplain deciduous forest, wet meadow vegetation and the shallow backwater lakes with aquatic vegetation [fig. 7].

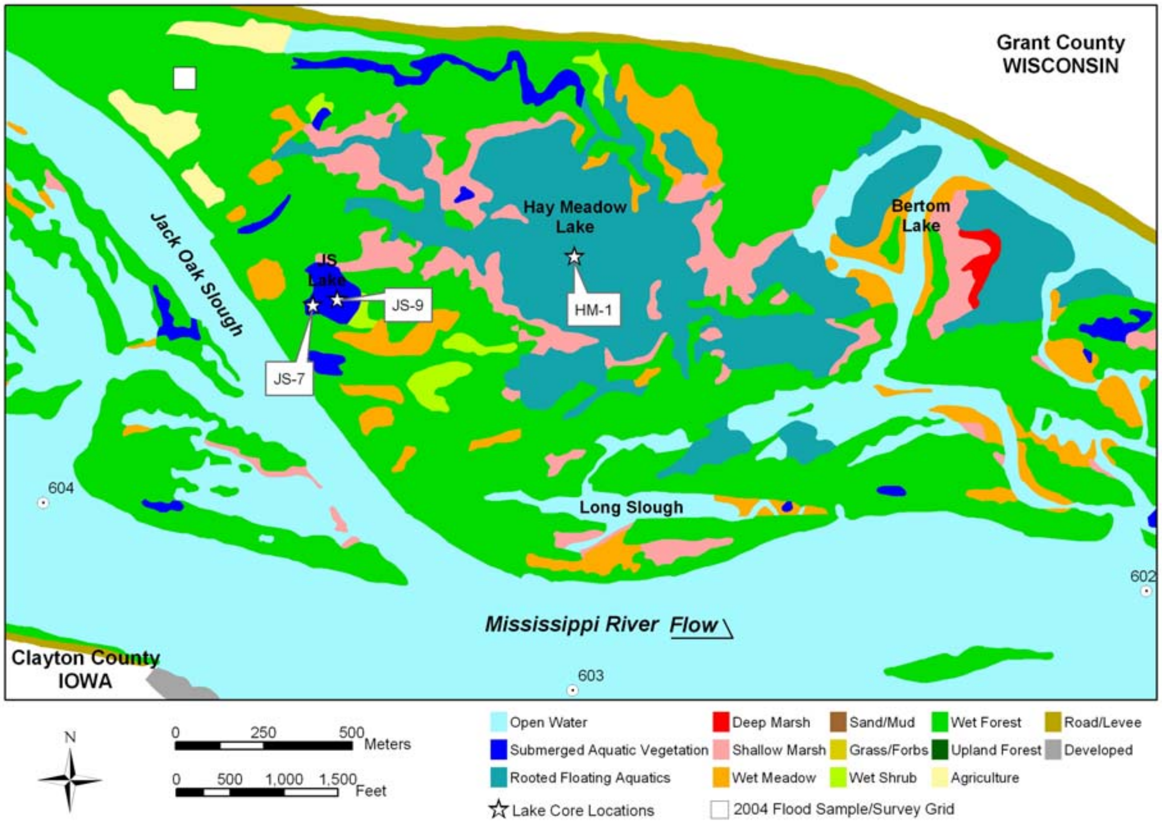


Figure 7. 2000 land cover for the study area. (Data source: Upper Mississippi Environmental Sciences Center)

The study area is part of the 94,300 hectare [233,000 acre] upper Mississippi River Wildlife and Fish Refuge (Anfinson, 2003). It has been identified as an area of ecological concern based on current and predicted future rates of sedimentation (West Consultants, 2000). Lock and Dam 11 created or expanded the floodplain lakes, but it is also responsible for their degradation and ecological decline through impoundment, sediment transport capacity reduction and rapid sedimentation.

Currently the lakes are very shallow. JS lake had a below ice water depth of only 0.52 meters [1.71 ft] and Hay Meadow Lake had a depth of 0.59 meters [1.94 ft] on February 28th, 2004. If the ice surface of the lakes at the time the depth measurements were made was equal to the river stage at river mile 603 (linearly interpolated from the Cassville and the Lock and Dam 11 gages), JS Lake and Hay Meadow Lake are estimated to have depths of only 0.37 meters [1.21 ft] and 0.44 meters [1.44 ft] below the flat pool elevation (183.79 m, 603.0 ft). The shallow depths of these lakes make them poor overwintering habitat for fish such as largemouth bass and bluegills. Fish are unable to migrate within or between the lakes, and lack of flow and decomposing vegetation cause low dissolved oxygen levels (Janvrin, 1998).

Water depth, flow velocity and sediment delivery to the lakes are highly dependent on river stages. Minor changes in river stages have a major effect on the aerial extent of each lake's shoreline and flow through the lakes [fig. 8]. Typically the UMR experiences annual floods in the springtime associated with snowmelt, though large summer floods may also occur as a result of excessive rainfall over a large region of the UMR watershed, as was the case for the 1993 flood (Knox and Daniels, 2002; Knox, 2003). Spring floods can be very large when snowmelt is combined with rainfall as was the case in 1965 during the largest flood on record for Pool 11 (Paulhus and Nelson, 1967).

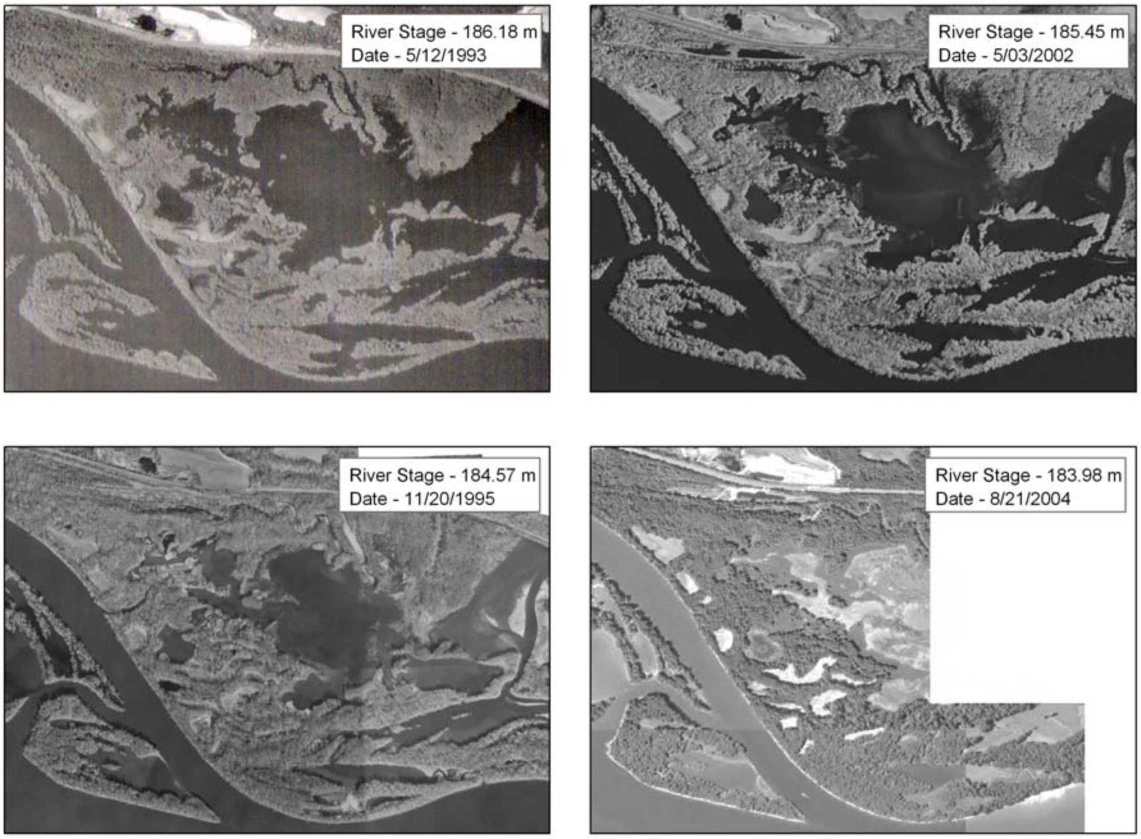


Figure 8. Comparison of river stages at the study site. (elevations interpolated from Cassville and Lock and Dam 11 stage data)

The area of the floodplain investigated for patterns of sedimentation and erosion after the June 2004 flood is located northwest of JS Lake and Hay Meadow Lake [fig 6]. It was chosen because it was flooded with at least one meter of water and because substantial flow moved through the site during the flood [fig. 9]. The site was also chosen because of its relatively easily identifiable sediment deposits [fig. 11] and representative floodplain topography [fig. 10]. The site has a minor swale running through it bordered by higher areas on either side. The swale serves as a conduit for higher velocity water during flood events. A large log jam and several smaller brush jams are located within the swale and influence flow velocity and direction.

Figure 9. a) Floodwaters moving through the area near where the 2004 floodplain deposits were collected (photo taken by author 6/19/04). b) Height of the 2004 flood as seen by watermarks on trees near floodplain sampling site (photo taken by author 8/19/04).

Figure 10. Site of the 2004 post-flood survey. Note the swale with few trees at the center of the photograph that acts as channel during floods and the large logjam located in the right-center of the photograph that influences flow velocity, direction and sediment deposition. (photo taken by author 10/30/04).

Figure 11. Flood deposit collected after the 2004 June flood on the UMR. (photo taken by author 8/19/04)

4.2. Methodology

4.2.1 Fieldwork

In order to compare and contrast the rates, processes and variability of sedimentation in a contiguous and an isolated backwater, four sub-aqueous sediment cores were extracted from the backwater lakes using a 7.62 cm [3 in.] diameter piston corer. These cores were extracted on February 2, 2004, while ice covered the lake, providing an optimal platform from which to work. Two cores were extracted from each lake with the intent that the duplicate cores would be used for wet bulk density analysis. The cores were collected from locations identified as floodplain depressions prior to the closure of lock and dam 11 on the Brown's survey maps and photographs [fig. 5]. By collecting cores from the deeper floodplain areas it is thought that a thicker and more pronounced depositional record would be obtained as a result of sediment focusing and infrequent drying. The cores from Hay Meadow Lake may have been taken just outside of the floodplain depression based upon the georeferenced Brown's Survey photographs and GPS coordinates taken during coring.

The duplicate core taken from JS Lake was too short and compacted to be used for wet bulk density analysis and is not discussed. One core from JS Lake, (JS-9) and one from Hay Meadow Lake (HM-1) were subdivided on site into one centimeter increments. The duplicate cores were collected whole and transported back to the University of Wisconsin-Madison Geomorphology Lab.

During June 2004 there was a minor flood [fig. 12] that inundated much of the back swamp of the study area. The flood deposited an easily identifiable layer of silty very fine sand with a fine drape of silt and clay [fig.11]. On October 30, 2004, an intensive survey of a 36x21 meter section of the floodplain was conducted. Local elevations were measured at three meter intervals along five 36 meter transects with a total survey station and the 2004 flood deposit thickness was measured at all survey points along four of the five transects. At the majority of the survey points, a surface sample of the 2004 flood sediment and pre-flood sediment was collected for analysis in the University of Wisconsin-Madison Geomorphology Lab.

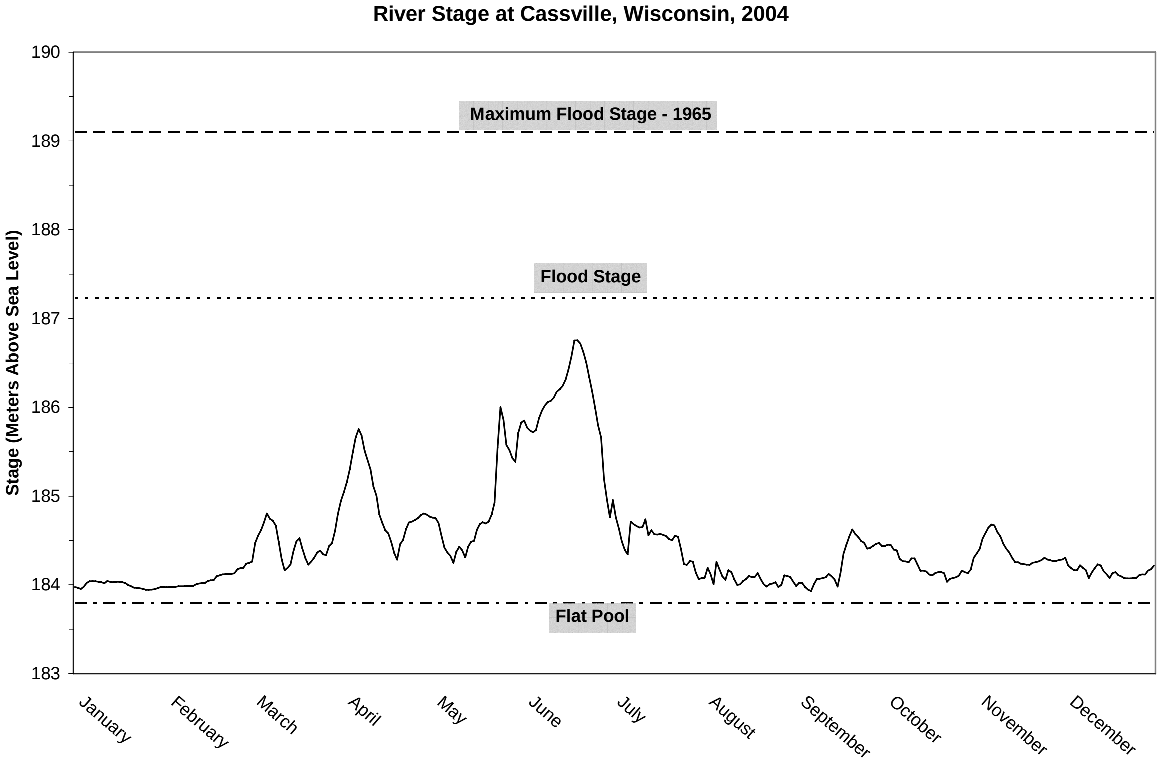


Figure 12. 2004 river stage recorded at Cassville, Wisconsin. (Data Source: U.S. Army Corps of Engineers)

4.2.2 Labwork – Sub-Aqueous Cores

The two sub-sampled cores, JS-9 and HM-1, were analyzed for particle size, percent organic matter, and percent carbonates (calcite and dolomite). HM-1 was also analyzed for ^{137}Cs. JS-9 was not analyzed for ^{137}C because a core with similar properties, JS-7, taken by Jim Knox and his assistants (L. Theis, T. Tennessen, R. Enright) in the fall of 2003 from within the shallow edge of JS Lake was analyzed for ^{137}Cs. The duplicate core taken at Hay

Meadow Lake, HM-2, was analyzed for wet bulk density. These lab analyses were used in an attempt to identify stratigraphic age markers within each core. They were also undertaken in an attempt to understand the processes affecting sedimentation within each of the backwater lakes. The analyses conducted on the different cores were used in conjunction to gain a better understanding of each lake's sedimentary history. As was seen in the review of prior studies, the use of only one method to investigate sedimentation rates is not sufficient. There needs to exist an understanding of what type of sediment is being deposited, when it is being deposited and how rates of sedimentation have changed over time, not simply the rate of sedimentation over a specific time period .

The pipette method adapted by Leigh (1991) and Day (1965) was used to analyze grain size from the JS-9 and HM-1 cores in approximately one centimeter increments. It has been shown that grain size analysis can provide a detailed flood history of the backwater lakes. Deposits of sand (2.0-0.063mm) indicate times of higher energy floods, while silt (0.002-0.063mm) and clay (<0.002mm) commonly indicate times of low energy and/or infrequent flooding (Theis and Knox, 2003; Knox and Daniels, 2002). Correlations can be made between sand layers and historical UMR stage records obtained from nearby stream gages, thus establishing age markers in the cores (Theis and Knox, 2003; Knox and Daniels, 2002; Knox, 2001).

Sand proportions or variability should also increase in floodplain sediments with the closing of Lock and Dam 11. The increased river stages after the dam began operation in 1937 made it easier for sand to be transported farther from the main channel (Knox and Daniels, 2002). Rogala *et al*. (1997) have also shown that grain size analysis can be used to identify the pre-impoundment surface. Sharp changes in grain size may potentially indicate the interface between the pre and post-impoundment surfaces.

Organic matter analysis was completed using loss on ignition at 550 ºC (LOI_{550}) modified from Heiri *et al*. (2001). A three centimeter sampling resolution was used for LOI_{550} and was shown to be of sufficient resolution to capture the trends in organic matter. LOI_{550} has been used in many studies to estimate organic matter content in lake and backwater sediments (Rogala *et al*., 1997; Rogala 1996; Heiri *et al*., 2001) and a strong correlation exists between LOI_{550} values and organic carbon (Konen *et al*., 2002) allowing for the comparison of trends between two cores analyzed by the different methods. Organic matter should rapidly increase after 1937 as a result of year-round high water tables creating biologically rich marshlands following the closure of Lock and Dam 11 and anaerobic conditions limiting organic matter oxidation and breakdown (Theis, 2002). Benedetti (2003) found that sand deposited during floods generally had low organic content and that floodplain enrichment with organic matter occurred between flood events. Times of flooding and rapid sediment deposition should be associated with lower organic matter values and periods of smaller or less frequent floods should be associated with higher organic matter values from the accumulation of decaying biomass.

Carbonate analysis was completed using the chittick method as presented by Machette (1986). A three centimeter sampling interval was used for the carbonate analysis and was shown to capture the trends in dolomite and carbonate within the core. Carbonate analysis can be used to estimate the influence of local tributaries draining the Wisconsin Driftless Area and Paleozoic uplands of northeastern Iowa on sedimentation within the backwaters. With the closure of the locks and dams, sediment from tributaries draining the loess-capped dolomite and limestone bedrock accumulated in greater amounts in the Pool 11 area (West Consultants, 2000) because the slackwater conditions of Pool 11 reduced the UMR's ability to transport tributary sediments downstream. These sediments have a higher carbonate content than sediments consisting mainly of glacial outwash and till (quartz and feldspars minerals) transported from pools upstream of Pool 11 (Theis, 2002).

Periods of slow sediment accumulation and pre-lock and dam sediments may have relatively lower carbonate concentrations as a result of carbonate leaching, though Theis (2002) found changes in percent calcite and percent dolomite were not always in phase with each other. Photosynthesizing aquatic vegetation has the ability to raise the pH of backwater lakes through the removal of CO_2 and cause calcite precipitation (Stewart, 1988; Borowitzka, 1984). Stewart (1988) found that floods temporarily dilute soluble alkalinity levels in streams, thus calcite precipitation may be reduced during periods of flooding and sediment deposition. Some algae species such as the *Chara* species are capable of causing calcium carbonate precipitation (Stewart, 1988; Borowitzka, 1984). *Chara* species have been found growing in several UMR backwaters (Yin *et al*., 2001; McFarland and Rogers, 1998).

Although the species composition and the water chemistry of Hay Meadow and JS lakes are unknown, it is known that the backwater lakes do have a high density of photosynthesizing macrophytic vegetation during the growing season that may play a role in calcite precipitation [fig. 13]. Calcite levels may see an increase after the construction of Lock and Dam 11 due to an increase in aquatic vegetation, with variations in post-lock and dam percent calcite being caused by flood events.

Figure 13. Dense coverage of macrophytes found at JS Lake (photo taken by author 8/19/04)

^{137}Cs analysis was completed for the HM-1 and JS-7 cores. Sediment from the HM-1 core was combined into ten centimeter intervals and sediment from JS-7 was combined into eight centimeter intervals. ^{137}Cs analysis was completed at the Wisconsin State Laboratory of Hygiene. ^{137}Cs can provide two identifiable dates within a sediment core based upon the fallout concentrations of ^{137}Cs. Fallout of ^{137}Cs began in 1954 with nuclear bomb testing and peaked from 1963-1964. ^{137}Cs fallout has been decreasing since 1963. Erosion of fine sediments tagged with ^{137}Cs and the subsequent deposition of the sediments in backwater lakes provides recognizable 1954 and 1964 marker horizons (McHenry *et al*., 1976). Because the sampling resolution is so low, ^{137}Cs will be used to verify dates assigned to the core based on the other analyses and to give a range in sedimentation rates at time intervals using the 1954 and 1964 dates.

The clod method (Singer, 1986) was used to analyze wet bulk density of the HM-2 core. Locating sharp changes in bulk density in floodplain sediments is a possible way to identify the pre-impoundment surface (Rogala *et al*., 1997). Bulk density has also been used to demonstrate how sediment compaction with depth can influence the interpretation of sedimentation rates (Theis, 2002).

4.2.3 Estimating Rates of Sedimentation

The traditional method for estimating rates of sedimentation based on the total depth of sediment accumulated over a known time period, measured in centimeters/year, will be given. Several identifiable depositional events are evident in each core based on the methods discussed above and it is therefore possible to see how rates of sedimentation have varied over time.

Bulk density has also been used to compensate for the compaction that occurs in buried sediment by the weight of overlying sediment (Theis and Knox 2003). One centimeter of sediment near the surface of a backwater is much less dense than more deeply buried sediments, thus rates of sedimentation may be under-represented at the bottom of a core or over-represented at the top of a core. Bulk density analysis of the HM-2 core will be used to adjust the sedimentation rates of the HM-1 core. Both cores were taken within meters of each other, so they should have the same increase in bulk density with depth.

Core lengths are adjusted based on the method used by Theis (2002). The bulk density measured at ten centimeter intervals in HM-2 was plotted and a regression equation for only the fine sediment has been used to calculate the bulk density for each one centimeter sampling interval of HM-1 [see Appendix 1]. Only the silt-dominated portion of the core is used because there is a sharp increase in bulk density with the sandy sediments, and paleosol evidence indicates that only the silt-dominated sediment is post-lock and dam sediment.

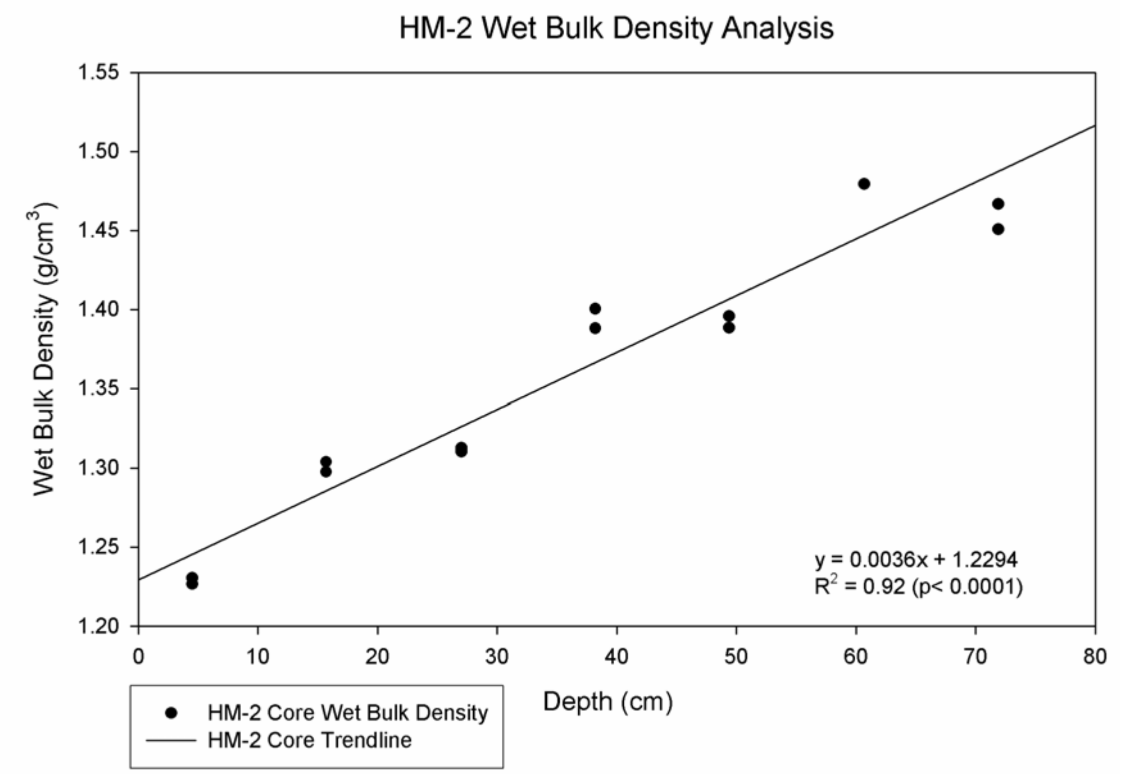


Figure 14. Wet bulk density analysis and regression equation from HM-2 used to compute wet bulk density and modified sedimentation rates for HM-1.

Theis and Knox (2003) showed that by taking the ratio of each one centimeter sampling interval's actual bulk density to the core's minimum, maximum and mean bulk densities it is possible to determine the minimum, maximum and mean rate of sedimentation if bulk density were constant with depth. For example, by using the minimum bulk density ratio it is possible to determine the maximum length each one centimeter interval would have if each interval's bulk density was equal to the minimum bulk density. By summing the new lengths for each interval based on the minimum bulk density ratio, a maximum potential rate of sedimentation is determined for HM-1.

Because bulk density changes with depth, sedimentation rates are also expressed in grams per square centimeter of the surface per year [(grams/cm^2)/yr] as an alternative to the traditional method of describing sedimentation rates in cm/yr. This rate provides the average mass of sediment deposited on the floodplain surface per year during the study period. To obtain this rate, the interpolated bulk density for each one centimeter increment in HM-1 is multiplied by the volume of a one centimeter increment in the 7.62 centimeter diameter core barrel (45.60 cm^3). The resulting mass of each one centimeter increment of the core is then added together for the post lock and dam sediment. The total mass of post-lock and dam sediment in the core is then divided by the area of the core barrel and the number of years in the post lock and dam period (1938-2003 → 66 years). While several other studies have represented rates from single floods using this method (Walling and He, 1998; Asselman and Middelkoop, 1995), the method was first used to describe sedimentation rates in the backwaters of the UMR over longer time periods by Theis and Knox (2003).

4.2.4 Labwork – 2004 Flood Samples

The floodplain samples collected after the 2004 flood were analyzed for percent sand and organic matter (LOI$_{550}$). The samples were divided into the 2004 flood deposits and the pre-2004 sediments. For consistency, only the upper three centimeters of the pre-2004 flood surface sediments were used in the percent sand and organic matter analyses.

By comparing the spatial variability in the thickness of the 2004 deposits, the amount of sand carried by the floodwaters, and the organic matter of the 2004 deposits, it is possible to gain a better understanding of how floodplain microtopography and large woody debris influence flow patterns and floodplain deposition. A comparison of the pre-2004 flood surface sediments and the 2004 flood sediments is also made to understand the evolution of the floodplain surface.

The computer program Surfer was used to interpolate surfaces based on the elevation data, the 2004 flood deposit thickness, and the 2004 flood and pre-2004 flood sediment percent sand and percent organic matter. Surfaces were interpolated using the kriging method. Kriging provided the best surface representation and has been used to interpolate surfaces in other floodplain sedimentation studies (Middelkoop and Asselman, 1998; Asselman and Middelkoop, 1995).

Chapter 5 – Results and Discussion

5.1 Analysis of Backwater Cores

5.1.1 JS-9 and JS-7 Results

The isolated backwater from which JS-9 was collected is located approximately 120 meters [400 ft] from Jack Oak Slough, a large secondary channel of the Mississippi River [fig. 3]. On October 10th, 2003, Jim Knox and assistants surveyed the elevation profile from Jack Oak Slough's shoreline to the top of the cutbank and over to the edge of JS Lake [fig. 15]. The top of the cutbank is labeled JS-2 and the edge of JS Lake, where Knox collected a core for lab analysis, is labeled JS-7.

Based on the October 10th, 2003 elevation of the cutbank and historical river stages for river mile 603.5 (linearly interpolated from stage data measured at the Cassville and Lock and Dam 11 gages) only nine floods since 1935 have been sufficiently high to flow overbank at JS-2 [table 2]. Because the elevation of the natural levee at JS-2 increases with each overbank flood, some historical floods may have been able to flow overbank at JS-2 that would not have been of sufficient magnitude to flow overbank based on the 2003 elevation. The relative magnitude of the overbank floods is represented in a graph of pool stages recorded at Lock and Dam 11 [fig. 16].

Smaller floods have reached JS Lake indirectly through breaks and low areas in the natural levee northwest of JS-2, though they would not have been of sufficient magnitude to transport significant quantities of sand across the floodplain to the JS Lake core sites. Lower magnitude floods may also deliver water and sediment to the isolated backwater through a low area connecting Hay Meadow and JS Lakes, though JS Lake is completely isolated during flat pool conditions [fig. 8].

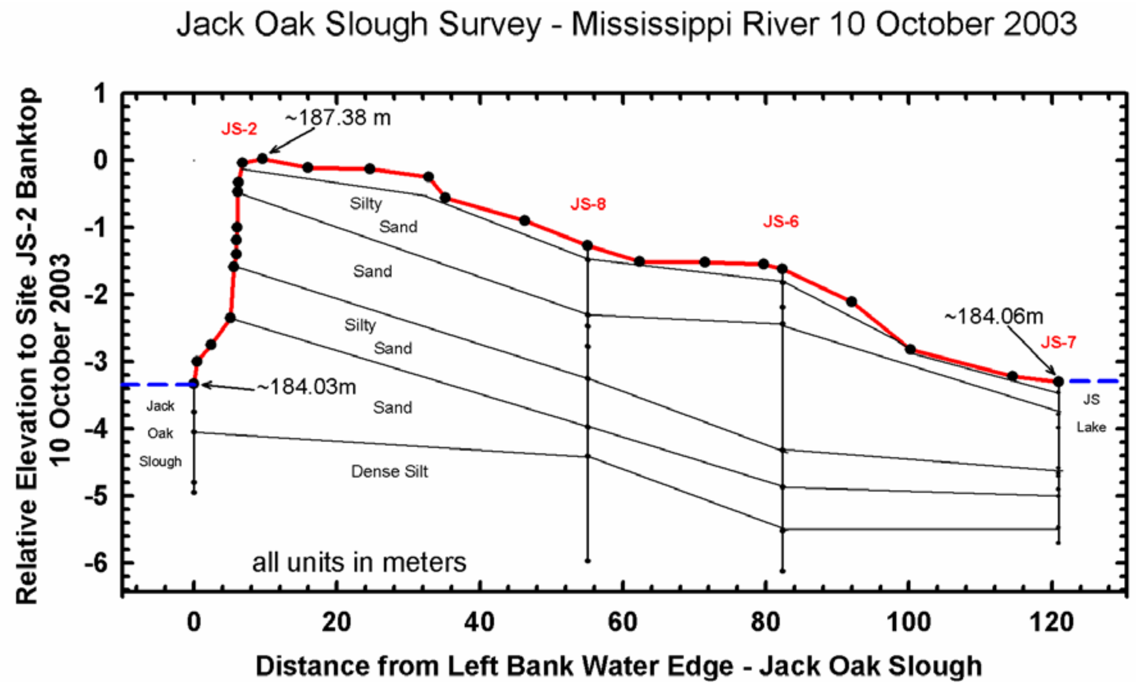


Figure 15. Cross-section from Jack Oak Slough to the edge of JS Lake where JS-7 and JS-9 were collected. (cross-section provided by J.C. Knox, modified by author, elevation data estimated from linearly interpolated stage data recorded at Cassville, Wisconsin and at Lock and Dam 11)

Overbank Floods at JS-2*	Date of Maximum Stage	Flood Stage Elevation at RM 603.5 (meters asl)**	Flood Stage Elevation (m) above JS-2 Cutbank (~187.38m)	# of Days Flood Overbanked at JS-2
1	4/25/1965	188.86	1.48	~18
2	4/21/2001	188.34	0.96	~27
3	6/30/1993	187.90	0.52	~17
4	4/23/1969	187.75	0.37	~11
5	4/22/1951	187.69	0.31	~13
6	4/241952	187.65	0.27	~13
7	4/16/1997	187.63	0.25	~10
8	5/5/1975	187.56	0.18	~7
9	4/11/1967	187.45	0.07	~6

* Overbank Floods based on the 2003 JS-2 bank elevation surveyed by J.C. Knox, 10/10/03.

** Flood stage elevations at river mile 603.5 linearly interpolated from Cassville and Lock and Dam 11 Gages.

Table 2. Floods on the upper Mississippi River, Pool 11, since 1935 of sufficient magnitude to overbank and inundate JS-7 and JS-9 core sites based on the 2003 surveyed elevation of JS-2.

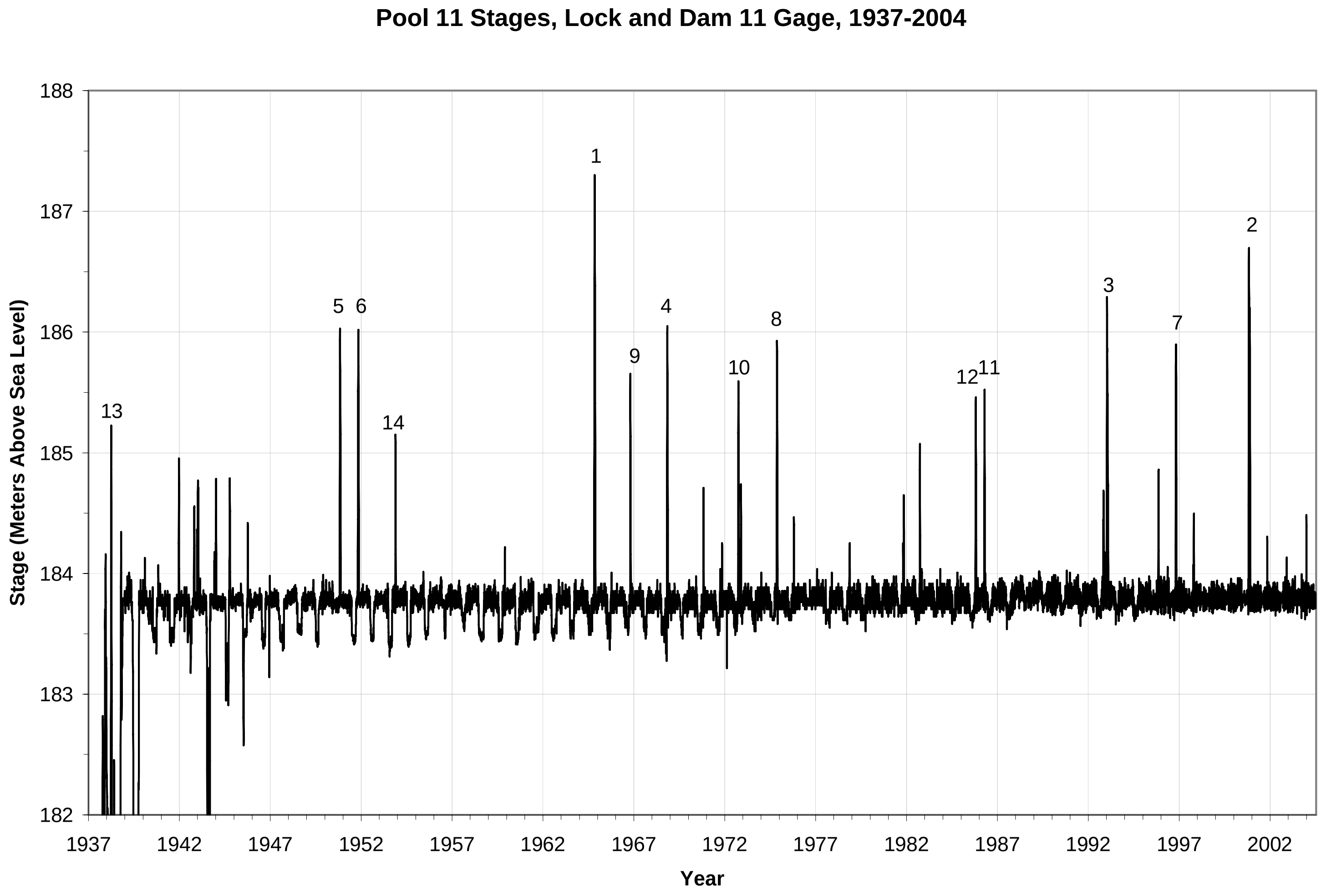


Figure 16. 1937-2004 pool stages as recorded at Lock and Dam 11, 20.5 river miles [33 km] downstream from JS Lake. Numbers 1-9 coincide with the floods capable of overbanking at JS-2 based on the 2003 banktop elevation and numbers 10-14 are floods that may have been able to overbank at JS-2 in the past. (Data Source: U.S. Army Corps of Engineers)

Pool 11's main channel is primarily composed of sandy bed material (Moody, 1997b). Large overbank floods are usually recorded in the sediment stratigraphy as deposits of fine and very fine sand near the main channel of the UMR. The interpretation of the sediment stratigraphy and correlation with individual floods or groups of floods has been used in several prior studies (Knox and Daniels, 2002; Theis and Knox, 2003; Knox, 2001) and will be an important factor in this discussion.

Particle size analyses were used in conjunction with percent organic matter and carbonate analyses for JS-9 to identify age markers within the sediment core [fig. 17]. JS-9 is a 75 centimeter core composed primarily of silty sediment with three prominent peaks of fine and very fine sand found near the bottom, middle and top of the core. Particle size, organic carbon, and ^{137}Cs analyses were completed for JS-7. The upper 104 centimeters of the JS-7 core is presented for comparison with the JS-9 core [fig. 18]. JS-7 is also composed primarily of sandy-silty sediment but with four prominent sand peaks. The particle size trends in each of the cores corresponds with three periods of overbank floods at JS-2 during the 72 year (1933-2004) stream gage record at Cassville, Wisconsin.

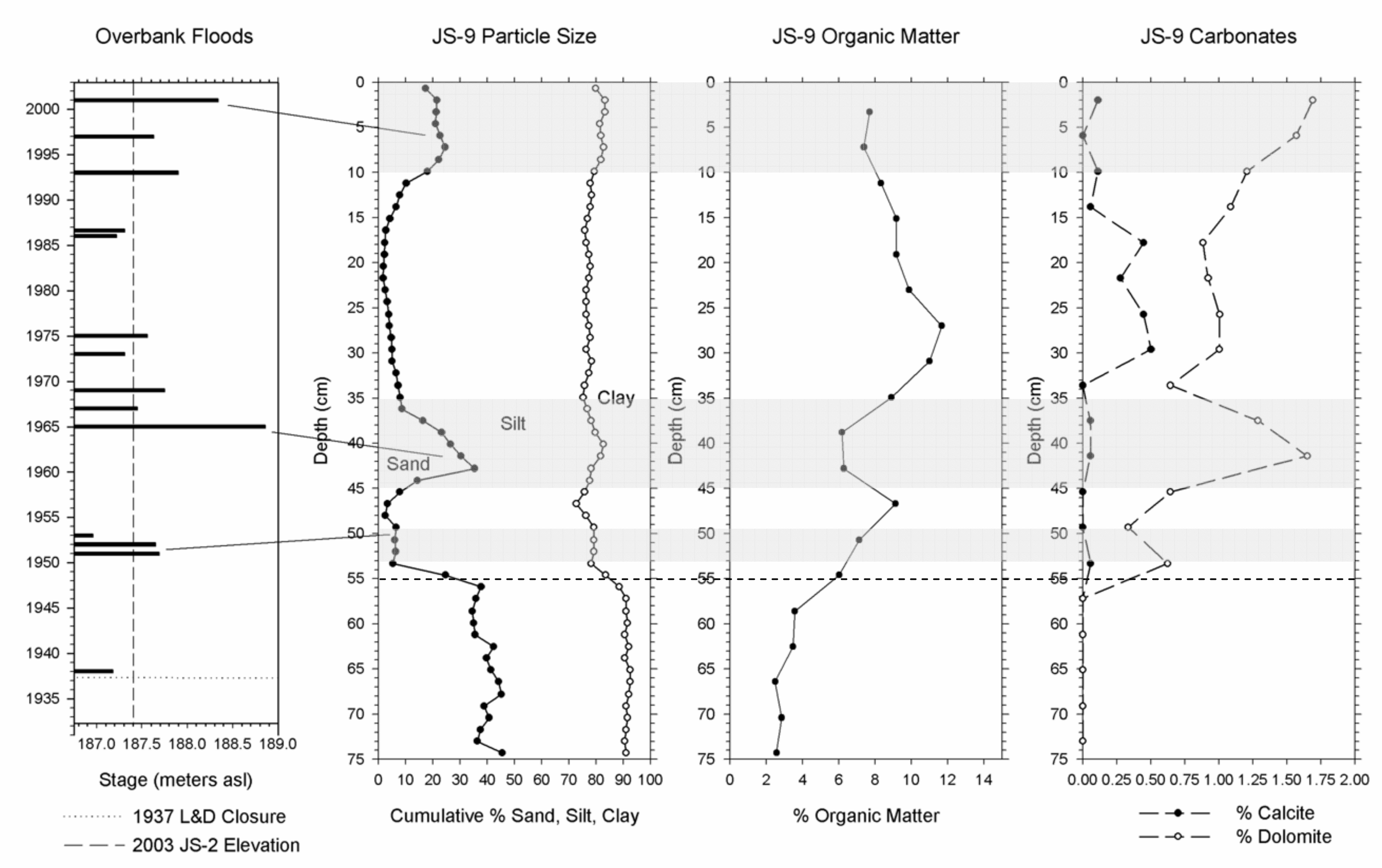


Figure 17. JS-9 lab analyses and correlation with the periods of overbank flooding at JS-2 from 1933-2004. Shading designates sediment deposited during the three periods of overbank flooding. The dashed line is the boundary between pre and post-lock and dam sediment. Core collected by author, 2/28/04.

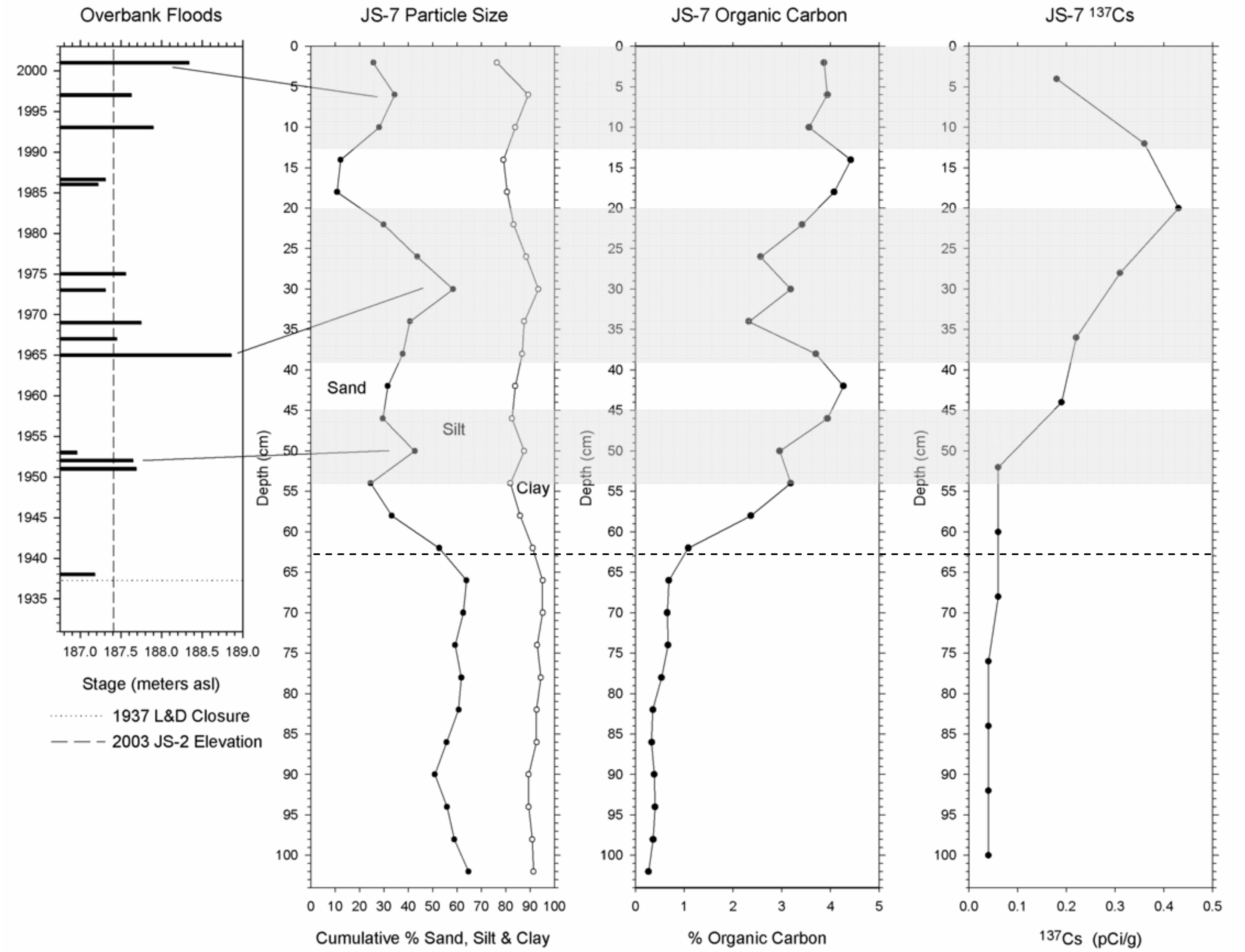


Figure 18. JS-7 lab analyses and correlation with the periods of overbank flooding at JS-2 from 1933-2004. Shading designates sediment deposited during the three periods of overbank flooding. The dashed line is the boundary between pre and post-lock and dam sediment. Core collected by J.C. Knox 10/10/2003. Particle size, organic carbon, and ^{137}Cs data provided by J.C. Knox.

The uppermost sand fraction in the top ten centimeters of JS-9 is predominantly associated with the 2001 flood, the second largest flood on record for Pool 11. This flood was of sufficient magnitude and duration [table 2] to transport large quantities of sand to the backwater lake. JS-7 has the same peak in sand in the upper ten to fifteen centimeters as JS-9. A slightly greater amount of sand from the 2001 flood appears to have been deposited near the shallow edge of JS Lake where JS-7 was collected than at the center of the lake where JS-9 was collected. Although the floodplain elevation is lower at JS-9, proximity to the source of the sediment is the dominant factor in the amount of sand deposited at each site, not sediment focusing.

Percent organic matter and percent organic carbon values drop significantly in sandy deposits associated with large floods at JS-9 and JS-7 respectively. Periods before and after the floods generally have a greater percent organic matter as a result of the accumulation of decaying organic matter between the depositional events (Benedetti, 2003). Episodes of fine sediment deposition associated with smaller floods or the tail end of larger floods also have higher percent organic matter levels than flood deposited sand. Organic matter preferentially adheres to finer sediments and drops out of suspension during lower energy flows. The pattern of higher organic matter content before a flood and in the fine sediment drape deposited at the end of a flood can be seen in the detailed analysis of a 2004 flood deposit [fig. 19]

The carbonate analysis for JS-9 shows a pronounced out of phase relationship between percent dolomite and percent calcite. While percent dolomite and percent sand increase contemporaneously, percent calcite increases at approximately the same depth organic matter increases [fig. 17]. Dolomite deposition appears to occur during flood events at this site while calcite precipitation occurs during periods of few floods or small magnitude floods when photosynthesizing vegetation influences water chemistry and causes calcite precipitation. The increase in percent dolomite in the JS-9 core is similar to the increase in percent dolomite in the coarser fraction of the 2004 flood sediment [fig. 19], reinforcing the connection between dolomite deposition and overbank floods. Because the figure 19 data represents a terrestrial floodplain site, calcite varies more closely with dolomite.

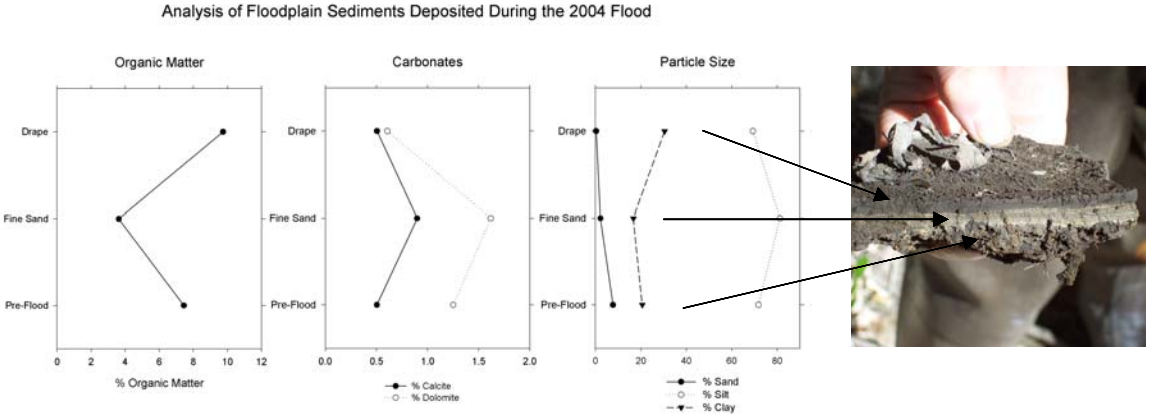


Figure 19. Patterns of organic matter and carbonates associated with sediment deposited during the 2004 flood. Similar patterns are found in the backwater lake cores and are believed to be associated with large magnitude floods and depositional events.

The period of decreased percent sand and higher percent silt in the JS-7 and JS-9 cores is likely associated with the period of relatively small floods in Pool 11 from 1966-1993 [fig. 17 and 18]. During this period, a lower percentage of sand and a higher percentage of silt would have been deposited by smaller overbank floods at JS-2 when smaller magnitude floods transported fine sediments to the lake through distributary floodplain channels. JS-9's closer proximity to the inlet from Hay Meadow Lake and its lower elevation may have contributed to the greater amount of fine sediment that accumulated at JS-9 than JS-7 between the 1965 and 2001. Sediment focusing of suspended sediment would be a more important factor at JS-9 than JS-7. During this period, organic matter and organic carbon increase in each core. This increase and the increase in calcite in JS-9 indicate this is a period of slower sediment deposition and lower magnitude, infrequent flooding.

The second peak in sand, found at approximately 43 centimeters depth in JS-9 and 30 centimeters depth in JS-7, is associated with the 1965 flood. The 1965 flood is the largest flood on record in Pool 11. It was also of sufficient magnitude and duration to contribute large quantities of sand to the isolated backwater during overbank flow [table 2]. Percent organic matter and percent organic carbon drop significantly at the same time the sand fraction increases within the JS-7 and JS-9 cores. As seen with the 2001 flood deposits, percent calcite drops to near zero during the 1965 flood while percent dolomite peaks during the flood.

Dating of JS-7 using ^{137}Cs provides strong support that the largest percent sand peaks do correspond with the 1965 flood. A peak in ^{137}Cs is located between 16 and 24 centimeters depth. Maximum fallout of ^{137}Cs occurred between 1963 and 1964. The 1965 flood was the first major flood after peak fallout with the capacity to deliver a significant quantity of sediment tagged with ^{137}Cs to JS-7. The 1963 and 1964 maximum flood stages were over two meters below the top of the cutbank at JS-2. The ^{137}Cs maximum comes at the tail end of the 1965 flood as fines fell out of suspension because ^{137}Cs is preferentially absorbed and retained by finer sediments (McHenry *et al*., 1976).

A minor peak in the percent sand is located below the 1965 flood deposit in JS-7 and is much less pronounced in JS-9. This peak is associated with the 1951 and 1952 floods. The fallout of ^{137}Cs began in 1954 and is not measurable in the profile until after the small sand peak. The 1951 and 1952 floods were the first major floods after the closer of Lock and

Dam 11 capable of clearing out the large volume of sediment accumulating in the channels of the UMR. A similar phenomenon has been documented at Lansing Site 2 on Mississippi River Island 146 near Lansing, Iowa (Knox, 2001).

The high sand fraction unit found in the cores below a depth of 55 centimeters in JS-9 and 63 centimeters in JS-7 represents pre-lock and dam floodplain deposition. The increase in organic content above the 55 and 63 centimeter levels is expected as Lock and Dam 11 raised water tables in Pool 11, created the backwater lakes, and caused anaerobic conditions that slowed the breakdown of organic matter accumulating in the lakes. Percent carbonates drop to zero below 55 centimeters in JS-9. Carbonates are expected to have been leached from the older pre-lock and dam surface when water tables were lower. Based on the markers identified as the pre-lock and dam period on figures 18 and 19, 55 centimeters of sediment have accumulated at JS-9 after the closure of Lock and Dam 11 and 63 centimeters have accumulated at JS-7. The increase in particle size variability found immediately above the designated 1937 horizon further supports the conclusion that the 55 centimeter and 63 centimeter depths mark the transition to pre-lock and dam floodplain sediments.

5.1.2 HM-1 Analysis

The Hay Meadow Lake core (HM-1) was collected from the contiguous backwater located approximately 1,000 meters east of Jack Oak Slough and approximately 720 meters from JS-9. Water flows through the contiguous backwater throughout most of the year and during most years as seen through a series of aerial photographs and through multiple visits to the site during 2004.

The sediment deposited at Hay Meadow Lake is much finer than at JS Lake [fig. 20]. The lack of significant sand deposition is caused by the contiguous backwater's increased distance from the main channel of the Mississippi River. Sand drops out of overbank flows closer to the main channel due to an immediate reduction in transport capacity while finer sediment can be carried greater distances across the floodplain. The analysis of HM-1 is not as straightforward as JS-9 and JS-7 as a result of the fine sediment accumulation and the lack of major stratigraphic markers. Because HM-1 is a contiguous backwater, deposition of fine sediment occurs in the lake during most years and large flood events may even scour out previously deposited sediments as seen at several other contiguous and isolated backwaters (Moody, 1997a; Moody, 1997b; Rogala and Boma, 1996).

If the sand fraction of the core is magnified, similar trends, as seen at JS-9 and JS-7, are evident. There are two peaks in very fine (63-125 μm) sand above the thick deposit of fine (125-250 μm) and very fine sand at the bottom of the core. The upper peak is likely associated with the 2001 flood (and possibly the 1993 and 1997 floods). The second peak at the 43 centimeter mark is associated with the 1965 flood. The 2001 and 1965 floods were likely the only two floods capable of transporting significant amounts of fine and very fine sand long distances across the floodplain.

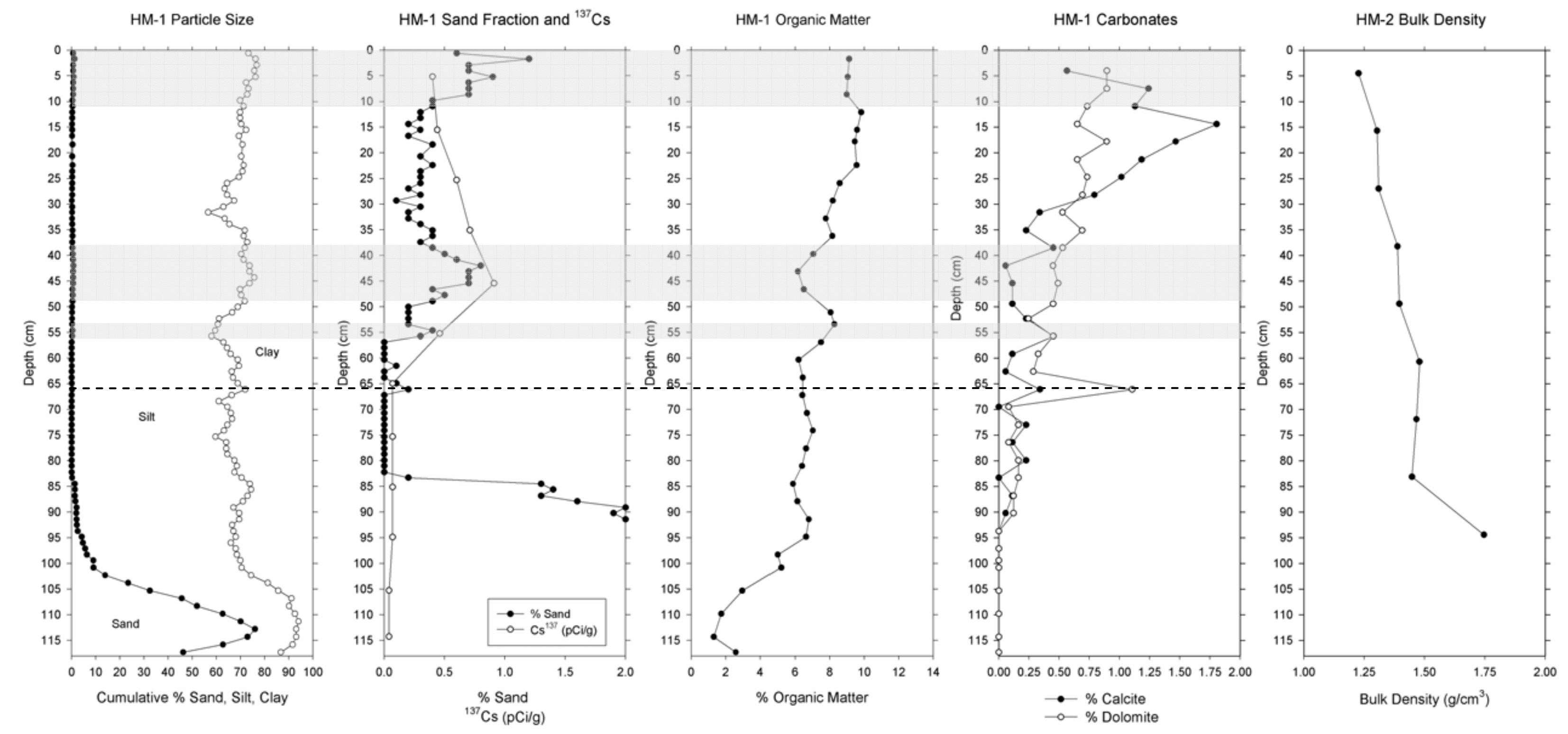


Figure 20. HM-1 lab analyses and HM-2 wet bulk density. Shading designates sediment deposited during the 2001, 1965 and 1951/52 floods. The dashed line is the boundary between pre and post-lock and dam sediment. Core collected by author 2/28/04.

Organic content in the core decreases at the same time the sand fraction increases at the identified 2001 and 1965 peaks, supporting the conclusion that large floods passed through the backwater lake. The decrease in percent organic matter is much smaller than during the major floods identified at JS Lake. The decrease may be smaller because less sediment was deposited during the flood events and/or because the fine sediment that was deposited was also associated with organic matter as seen in the drape deposited during the 2004 flood [fig. 19].

The peak in ^{137}Cs between 40 and 50 centimeters coincides with the peak in sand found at 43 centimeters, supporting the conclusion that the sand was deposited during the 1965 flood. The 1965 ^{137}Cs and sand peaks align better in HM-1 than JS-7 because primarily only fine sediment (silts and clays) was deposited during the 1965 flood at HM-1.

Percent calcite drops to minimum level at the same time percent sand reaches a peak value during the 1965 flood. Calcite increases during the period of smaller floods between the 1965 flood and the 1993 flood. At approximately the same time that percent sand increases near the top of the core, percent calcite experiences another major decrease.

The depth associated with the closure of Lock and Dam 11 is identified as 66 centimeters. An increase in the sand fraction begins at this point as a result of higher stages in Pool 11 and the increased ability for coarser sediment to be transported across the floodplain. A jump in the percent carbonates also occurs at this depth. The increased water levels in the lake have resulted in an increase of marshland in the vicinity of the HM-1 core. Changes in water chemistry by photosynthesizing macrophytes may have caused the increase in percent calcite. Percent carbonates in the sediments also likely increased after 1937 as a result of the increased ability of floodwaters to transport carbonate sediments to the lake.

Measurable levels of ^{137}Cs associated with 1954 begin between 50 and 60 centimeters depth, making it reasonable that the 66 centimeter depth is the transition point to pre-lock and dam sediment. Bed elevation surveys conducted in 1938 and 1951 also indicate that little sedimentation had occurred at the study site between 1938 and 1951 [fig. 21].

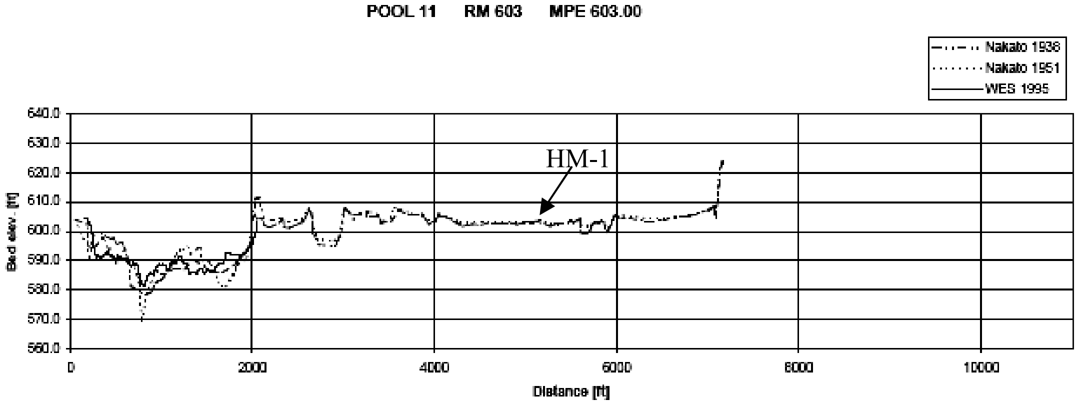


Figure 21. Bed elevation surveys at river mile 603 through Hay Meadow Lake. HM-1 experienced little sedimentation from 1938-1951, though some of the deeper areas were filling in rapidly (West Consultants, 2000)

It is difficult to say precisely when the silt and clay below 66 centimeters was deposited. The period 1850-1937 was a time of increased agriculture, mining and forestry in the drainage basins contributing water and sediment to Pool 11. This period is associated with an increased ability for sediments to reach the floodplain through more frequent flooding and an increased supply of sediments in the floodwaters due to mining and agriculture (Knox and Daniels, 2002; Knox, 2001; Knox, 1987). The silt and clay found between 66 and 84 centimeters may be associated with the 1850-1937 time period. The period 1880-1922 was relatively wet in the UMR valley with an increased occurrence of large overbank floods (Knox, 2001). These floods may have contributed much of the pre-lock and dam fine sediment. The 1929/30 Brown's topographic survey shows a small creek flowing into the area to the east of where HM-1 was collected. When this creek flooded, it may have deposited silt near Hay Meadow Lake. Unleached carbonates are found in the sediment above the 84 centimeter level, further supporting that the sediment may have been deposited by streams draining the Driftless Area with its carbonate bedrock and easily eroded unleached loess.

A second possibility is the sediment may have been gradually accumulating on the floodplain and in the small floodplain lake prior to Euro-American settlement. The silt may be a combination of pre-settlement and post-settlement accumulation. In either possibility, the sandy sediment found below the 84 centimeters level is the pre-settlement surface and may be former channel bottom sand or bar deposits. This site provides an example of when it is not appropriate to use Rogala *et al.*'s (1997) method of identifying the pre-impoundment surface simply by a sharp change in grain size or bulk density.

It is worthwhile to note that the organic content of the lake has been relatively high throughout historical times. As seen in figure 5, this core was taken in an area that was a floodplain depression prior to the closure of Lock and Dam 11. As a result, organic matter may have been accumulating throughout historical times, and its decomposition would have been slowed by the anaerobic conditions of a small ephemeral lake.

5.2 Discussion of Backwater Core Results

5.2.1 Sedimentation Rates

By combining multiple lab techniques it was possible to identify stratigraphic markers and individual events within a single core. The benefit of the detailed analysis is the ability to examine sedimentation rates during single events and over longer time periods. While many prior studies have looked at sedimentation rates in the UMR over the portions of the post-lock and dam period (Eckblad *et al*., 1977; Claflin, 1977; McHenry *et al*., 1984; Korschgen *et al*. 1987; Rogala *et al*., 1997; West Consultants, 2000), only a few have looked into rates and patterns at the event scale over the course of the entire post-lock and dam time period (Knox, 2001; Theis, 2002; Knox and Daniels, 2002; Benedetti, 2003).

Core	Time Period	Method	Rate	% of Total Post Lock & Dam Sedimentation
JS-9	1938-2003	Particle Size/Carbonates/Organic Matter	0.83 cm/yr	---
	1951 & 1952 Floods	Particle Size/Carbonates	~5 cm/yr	9.1
	1965 Flood	Particle Size/Carbonates/Organic Matter	~12 cm/yr	21.8
	2001 Flood	Particle Size/Carbonates	10-15 cm/yr	18.2-27.3
JS-7	1938-2003	Particle Size/Organic Carbon	0.95 cm/yr	---
	1951 & 1952 Floods	Particle Size/Organic Carbon	~8 cm/yr	~12.7
	1965 Flood	Particle Size/Organic Carbon	up to 28 cm/yr	up to 44.4
	2001 Flood	Particle Size/Organic Carbon	up to 15 cm/yr	up to 23.8
HM-1	1938-2003	Particle Size/Carbonates/Organic Matter	1.00 cm/yr	---
	1951 & 1952 Floods	Particle Size/Carbonates	1-2 cm/yr	1.5-3.0
	1965 Flood	Particle Size/Carbonates/Organic Matter	~12 cm/yr	~18.2
	2001 Flood	Particle Size/Carbonates/Organic Matter	5-10 cm/yr	7.6-15.2
	1954-2003	^{137}Cs	1.03-1.28 cm/yr	---
	1964-2003	^{137}Cs	1.02-1.22 cm/yr	---
	1954-1964	^{137}Cs	0.00-2.00 cm/yr	---
	1938-1954	^{137}Cs and Particle Size/Carbonates/OM	0.36-1.00 cm/yr	---
	1938-1964	^{137}Cs and Particle Size/Carbonates/OM	0.62-1.00 cm/yr	---

Table 3. Rates of sedimentation for the post-lock and dam period computed for the three core locations. Rates for individual floods are estimates based on the lab analyses presented in figures 17, 18, and 20.

Sedimentation rates have been computed for the post lock and dam period and for individual flood events. Stratigraphic bounds for individual flood events are approximated based on evidence derived from lab analyses of sediment cores. Rates from the ^{137}Cs analyses are only presented for HM-1 because it is thought that due to HM-1's grain size and associated conditions of nearly continuous flow, the rates are more time representative than at JS-7. Rates derived from ^{137}Cs analysis are presented as a range because a ten centimeter sampling resolution was used in the analysis. As can be seen in table 3, it is difficult to make between period comparisons based on ^{137}Cs sampling resolution. Future studies should also present sedimentation rates estimated from ^{137}Cs as a range if a coarse sampling resolution is used.

Post lock and dam sedimentation rates for the present study sites are lower than those previously reported at other backwater sites on the UMR [see table 1], suggesting the backwaters may not be disappearing as rapidly as originally thought. Theis and Knox (2003) and Benedetti (2003) found rates of sedimentation for isolated backwaters and floodplain sites in Pool 10 comparable to those of the present study. Long-term sedimentation rates here are similar to post-lock and dam rates found for some areas within Pool 11 (West Consultants, 2000; Nakato 1981b; USACE, 2002b), though high variability does exist between the adjacent backwaters. The 1938-1988 rates in Bertom Lake were nearly double that of Hay Meadow and JS Lakes. JS Lake's rates are lower because it is isolated from frequent flooding. Though Hay Meadow Lake is a contiguous backwater, its connection to the main channel is much further away than that of Bertom Lake. Sediment supply to Bertom Lake is greater because of more tributaries entering the lake and it is characterized by greater connectivity to the UMR.

Based on the estimated rates of sedimentation and their present depths, JS Lake and Hay Meadow Lake will be filled with sediment to the flat pool elevation within 40-45 years. Though many other studies have claimed similar rapid rates of backwater loss (McHenry *et al*., 1984; Eckblad *et al.*, 1977; Ritchie *et al.*, 1986), it is doubtful the backwaters will fill with sediment at a constant rate. Rates of sedimentation in backwaters have been shown to decrease with decreasing depth (Steffeck *et al*., 1980) and continued improvements in land use may slow backwater sedimentation. The high degree of spatial variability in sedimentation rates within an individual backwater also makes it difficult to apply the results from a single core to an entire backwater (Rogala and Boma, 1996). Some areas of the backwater may be disappearing more rapidly or more slowly than adjacent areas.

Even within the small backwater JS Lake, variability exists in the amount and type of sediment found, making it difficult to apply a timeframe for complete backwater disappearance. The higher rates of sedimentation near the main channel may cause the west margin of the lake to prograde eastward, though comparisons of aerial photos taken over the past 65 years (1940-2004) do not show any major changes in the shoreline of JS Lake [fig. 22]. Nearshore wave erosion limits terrestrial encroachment in many backwaters of the UMR (Rogala *et al*., 2003) and may be redistributing some of the sediment deposited during overbank floods at JS Lake. The lake does appear to have become shallower after the 1965 flood, but the position of the lake's shoreline has not changed. Backwaters in Pool 10 also show general stability in a review of historical surveys and photographs, though isolated backwaters were experiencing some gradual loss as a result of post-lock and dam sedimentation (Collins and Knox, 2003). Care must be taken when only using aerial photographs to estimate the degree of change occurring in backwater habitats because slight

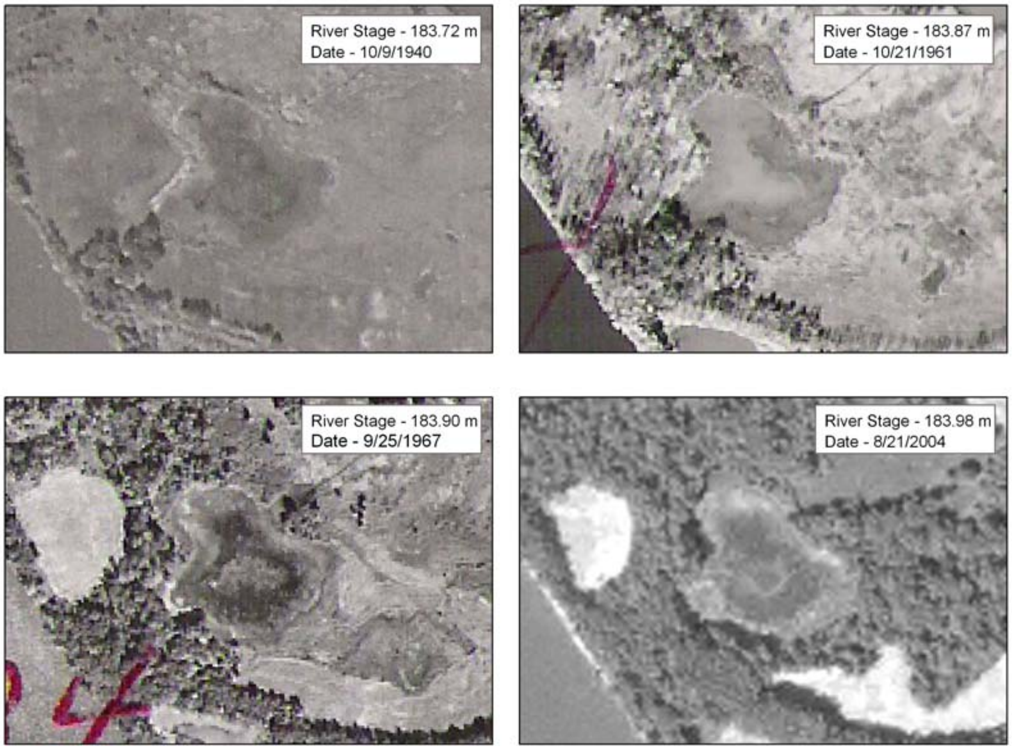


Figure 22. JS Lake near the flat pool elevation (183.79 m) over the past 65 years. Little change has occurred in the outline of the lake, though it has become much shallower.

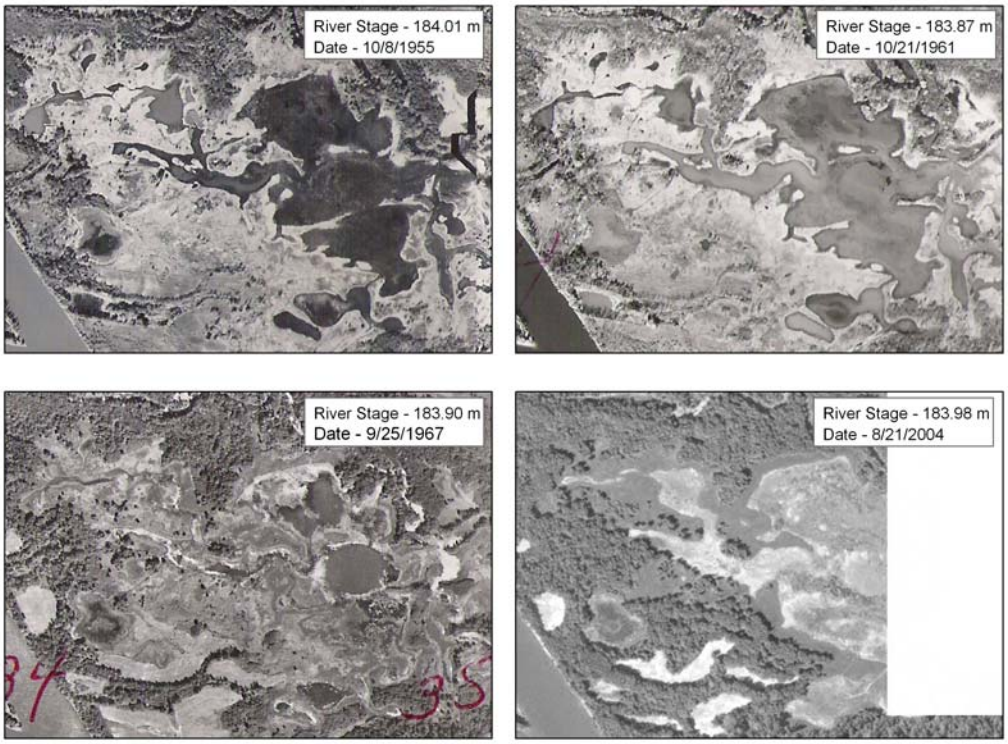


Figure 23. Hay Meadow Lake near the flatpool elevation (183.79 m) over the past 50 years. The lake has clearly become shallower following the 1965 flood.

changes in lake levels may heavily influence interpretations and may not account for the below water changes in lake depth.

The morphology of Hay Meadow Lake was also examined through a series of historical aerial photographs [fig. 23]. These images, taken during near flat pool elevations, show a distinct change from before the 1965 flood to after the 1965 flood. The 1961 and 1967 photographs were taken at the nearly the same time of the year and the river stage was virtually identical at the date of photography. Before the 1965 flood a greater amount of open water existed at Hay Meadow Lake. The sedimentation that occurred during the 1965 flood had a significant impact on the depth of the lake during low river stages. Homogenization of backwater bathymetry has been cited as a problem in backwaters across the UMR (West Consultants, 2000; Nakato, 1981b; Bhowmik *et al.*, 1986) and this process clearly appears to be happening at both Hay Meadow and JS Lakes. Hay Meadow Lake's connection to Bertom Lake also appears to have decreased since 1961 which could have a large impact on the reduction of flow through the lake and sediment deposition within Hay Meadow Lake.

Large overbank floods are the dominant geomorphic influence on sedimentation at JS Lake and also played a significant role in sedimentation at Hay Meadow Lake [table 3 and figs. 17, 18, 20]. The 1965 flood caused the greatest amount of sedimentation at all three core sites in this study, with JS-7 experiencing the greatest impact from the flood. While it is surprising that evidence of this flood is not recorded at several sites in Pool 10 (Benedetti, 2003) it is clearly recorded in the floodplain stratigraphy in Pool 9 (Knox, 2001).

The protected location of JS Lake behind the high natural levee may have helped to preserve the 1965 flood deposits. JS-7 had a higher percentage and a thicker depth of sand deposited during the 1965 flood than JS-9. The increased amount of sedimentation is reasonable because JS-7 is located closer to the main channel, and areas closer to the main channel typically display the largest magnitudes of deposition and coarser sediments (Walling and He, 1998; Middelkoop and Asselman, 1998; Theis and Knox, 2003).

Figure 24. 2001 sand splay extending from JS-2 towards JS-7. (photos taken 8/19/04 by author)

The 2001 flood had the second largest single event geomorphic impact at the three core sites. Theis and Knox (2003) and Benedetti (2003) reported finding thick deposits of sand on the floodplain associated with the 2001 flood in Pool 10. Rogala *et al*. (2003) also reported that terrestrial areas bordering backwaters had high rates of sedimentation during the 2001 flood. A large sand splay was deposited by the 2001 flood leading from JS-2 towards the isolated backwater, indicating large overbank flows are capable of transporting sand to the isolated lake [fig. 24]. The splay's thickness decreases with distance from JS-2 towards JS Lake. Flow divergence on the floodplain side of the natural levee is likely responsible for the decrease in the amount of sediment deposited with distance from the levee and with the decrease in the percent coarse sediment deposited with distance from the levee. Similar patterns of sedimentation near natural levees have been found in other studies of floodplain sedimentation (Gomez *et al*., 1997; Middelkoop and Asselman, 1998; James, 1985; Gomez *et al*., 1995). If the splay remains sparsely vegetated, it may become a source of sediment for JS Lake during future overbank floods at JS-2.

The 1993 and 1997 floods may also have contributed to the backwater sedimentation, though their contribution is much smaller than the 2001 flood. After the 1993 flood, 3 centimeters of sedimentation was observed in the forested floodplain downstream of Hay Meadow Lake, northeast of the Bertom Lake boat landing (personal communication with J.C. Knox, 2005). Measurements by J.C. Knox (personal communication, 2005) indicate that 3-4 centimeters of floodplain deposition in Pool 11 was not uncommon for the 1993 flood, with a range of 2-5+ centimeters. Knox (2001) found that the 1993 and 1997 floods left significant deposits of sand on Pool 9's floodplain near Lansing, Iowa. In Pool 10 the 1993 and 1997 floods left behind much smaller deposits and had a much more limited geomorphic impact on the floodplain than the 2001 flood (Benedetti, 2003). The 1993 and 1997 floods had lower stages, were of shorter duration and had a greater hysteresis between the peak discharge and peak suspended sediment concentration than the 2001 flood (Benedetti, 2003). At the Lansing site, the 1993 and 1997 flood stages were approximately 1.5 meters above the floodplain surface. At the natural levee above JS-9 and JS-7 the 1993 and 1997 floods were only 0.25 and 0.52 meters [0.82 and 1.71 ft] above the surface, reducing the potential for transportation of coarse sediment from the main channel onto the floodplain behind the natural levee.

5.2.2 Temporal Trends in Sedimentation Rates

Though several studies argue that sedimentation rates have been reduced since the middle 20th century due to improved land management (McHenry *et al*., 1984; Knox, 1987; Anfinson, 2003; West Consultants, 2000; Bhowmik and Adams, 1989; Benedetti, 2003) this trend is not obvious in either of the lakes. Rates of sedimentation in the backwaters remain an order of magnitude greater than pre-settlement rates (Knox, 2001; Benedetti, 2003). The episodic nature of sedimentation in JS-7 and JS-9 makes it difficult to identify temporal trends in sedimentation rates. JS-9 and HM-1 both have high sedimentation rates between the 1966 and 1993. The rates of sedimentation based on ^{137}Cs levels for HM-1 are inconclusive. The data suggest that sedimentation at the lake has decreased with time if the maximum rates are used and increased with time if the minimum rates are used.

The time period of sampling is an important factor when estimating rates of sedimentation at these backwaters or any other floodplain site. UMR flood magnitudes and recurrence frequencies have not been constant through time. Analysis of discharge data on the UMR at Winona, Minnesota from 1879-2002 shows an unusually high occurrence of large overbank floods has occurred since 1950 on the UMR. (Knox, 2000; Knox, 2003). Climate and atmospheric circulation patterns appear to be the driving force behind the variability of large floods. Over longer timeframes, the onset of global warming and dry periods are often associated with frequent large floods, followed by periods of smaller floods (Knox, 2003).

The high rates of sedimentation experienced at the study sites may be a response to the anomalously high frequencies of large floods occurring since 1950. Rates of overbank deposition on the UMR floodplain have varied over the past 125 years in response to the occurrence of large overbank floods. Above average precipitation and a high occurrence of large overbank floods caused similarly high rates of sedimentation during the 1880-1922 and post-1950 periods while lower rates of sedimentation occurred during the drier 1920’s and 1930’s. (Knox 2001). Future changes in atmospheric circulation patterns may lead to smaller magnitude infrequent overbank flooding and reduced sedimentation. By averaging sedimentation over longer periods that include multiple climate and land use regimes, sedimentation rates will likely be lower than what is represented by only the post lock and dam record.

5.2.3 Land Cover Changes

Land cover changes at the study site have also likely played a role in sediment transport and deposition during overbank floods. While deciduous forest vegetation is currently the predominant land cover around the backwaters, floodplain vegetation has not always been as dense over the past century [figs. 22 and 23]. The present day forested floodplain may reduce the quantity of sediment transported to the floodplain lakes by increasing the floodplain’s hydraulic roughness and creating depositional zones behind flow obstructions such as trees and debris dams.

Vegetation cover and debris dams influence floodplain sediment transport, deposition and storage as demonstrated by a small flood during June of 2004 [section 4.3] and by Jeffries *et al*. (2003). Observations by J.C. Knox (personal communication, 2005) indicate that during the 1993 flood up to 60 centimeters of sandy sediment was deposited as water flowed across the open field to the northwest of Hay Meadow Lake and entered the forest [fig. 6]. Prior to the present day dense vegetation cover, the floodplain surface’s hydraulic roughness would have been lower and sediment transport capacity greater. A greater proportion of overbank flood sediment may have been delivered to the lakes prior to re-growth of the floodplain forest.

5.2.4 Wet Bulk Density

Because sedimentation rates can be skewed by sediment compaction with depth, wet bulk density analysis was used to compensate for the compaction in the HM-1 sediment record and to provide an alternative method for presenting sedimentation results. Based upon the wet bulk density of HM-2 and the methods outlined in Section 4.2.3, the rates of sedimentation for HM-1 were adjusted as shown in table 4.

Wet bulk density clearly has an affect on the estimated rate of sedimentation. This effect can be shown if HM-1's core length is adjusted by making the wet bulk density constant for HM-1's post-lock and dam sediment. The length of each one centimeter slice of post-lock and dam sediment in the HM-1 core (66 centimeters total) was adjusted using the maximum, minimum, and mean wet bulk densities interpolated from HM-2. Assuming the maximum and minimum wet bulk densities represent endpoints in the range of wet bulk density possibilities, the interpolated wet bulk density for each one centimeter increment of the core was divided by the maximum, minimum, and mean wet bulk density to provide an adjusted length for each one centimeter increment (see Appendix A). These values were summed to provide an adjusted core length for the post-lock and dam sediment.

The estimated adjusted core length using the maximum wet bulk density ratio is 60.7 cm, the estimated adjusted core length using the minimum wet bulk density ratio is 72.3 centimeters, and the estimated adjusted core length using the mean wet bulk density ratio is 66.0 centimeters. Based on these adjusted core lengths, post lock and dam rates of sedimentation at HM-1 vary by as much as 0.18 cm/year. While this amount of variability may not seem extraordinary, it is important when carried out over longer time periods or when attempting to predict the life of projects such as the U.S. Army Corps of Engineers habitat rehabilitation projects in Bertom and McCartney Lakes.

Core	Time Period	Method	Rate
HM-1	1938-2003	Unadjusted Sedimentation Rate	1.00 cm/yr
		Maximum Wet Bulk Density Ratio Sedimentation Rate	0.92 cm/yr
		Minimum Wet Bulk Density Ratio Sedimentation Rate	1.10 cm/yr
		Average Wet Bulk Density Ratio Sedimentation Rate	1.00 cm/yr
		(grams/cm^2)/year	1.35 g/cm^2/yr

Table 4. Modified sedimentation rates at Hay Meadow Lake using wet bulk density analysis from the HM-2 core.

Theis and Knox (2003) presented sedimentation rates in (grams/cm^2)/year for isolated backwaters of Pool 10 accumulating predominantly silty sediment. This rate, (grams/cm^2)/year, represents the mass of sediment accumulated at the lake bottom near each core site in a given year. To obtain this rate, the interpolated bulk density for each one centimeter increment in HM-1 is multiplied by the volume of a one centimeter increment in the 7.62 centimeter diameter core barrel (45.60 cm^3). The resulting mass of each one centimeter increment of the core is then added together for the post lock and dam sediment. The total mass of post-lock and dam sediment in the core is then divided by the area of the core barrel and the number of years in the post lock and dam period (1938-2003 → 66 years).

This alternative rate reduces the impact sediment compaction has on estimated sedimentation rates when using a rate of centimeters/year as seen in table 4 and described above. The change in bulk density with depth at HM-2 was nearly identical to the Pool 10 sites (Theis, 2002). By taking wet bulk density into account in both our studies, a more accurate comparison of sedimentation rates between the two study sites is possible. The sites in Pool 10 experienced slightly lower rates of sedimentation than the contiguous backwater in Pool 11 because they are more isolated from flow and sediment delivery during the year.

It is hoped that future studies of sedimentation will also account for sediment compaction and use wet bulk density to enable better comparisons of results.

5.2.5 Sediment Source

When attempting to reduce sedimentation within individual backwaters, it is important to know what the major sources of sediment are. Carbonate analysis was used in part to investigate the source of sediments being deposited in the study area. Streams draining the tributary basins underlain by limestone and dolomite bedrock and capped with unleached loess should have a higher component of calcite and dolomite in the sediment being transported than the sediment from the main channel of the UMR. The increase in low water stages after the construction and operation of Lock and Dam 11 caused many tributaries to deposit their sediments in the calm waters of the newly created backwaters.

The percent calcite and dolomite for HM-1 and JS-9 were very low, suggesting local tributaries are not a major source of sediment delivered to these backwaters. This finding is not surprising because no major tributaries drain into the areas near JS-7, JS-9 and HM-1. Theis and Knox (2003) found much higher carbonate levels in their study of Bagley Bottoms, Pool 10, than was found in this study. Two moderately sized tributaries flow into the vicinity of the Bagley Bottoms core sites and likely caused the much higher carbonate concentrations in their study.

Much of the sediment being delivered to the backwaters in the study site is from the main channel of the UMR. Overbank floods supply the bulk of deposition at JS Lake while overbank floods and flow from Crooked Slough and several smaller distributary channels deliver sediment to Hay Meadow Lake. The dominance of the UMR supply of sediments is further indicated by the large unvegetated delta growing into Bertom Lake from a side channel immediately downcurrent of Hay Meadow Lake [fig. 4]. The carbonate results are consistent with sediment supply estimates conducted by the USACE. Upland erosion contributes an estimated 12.2 percent of the sediment deposited in the backwaters adjacent to the study site while the UMR supplies the remaining 87.8 percent (USACE, 1989).

The U.S. Army Corps of Engineers has attempted to slow the rapid filling of Bertom Lake and McCartney Lake by placing a closing structure in the side channel entering Bertom Lake where the delta is forming (USACE, 2002b). Recent results are inconclusive on how well the structure has slowed sedimentation in the lakes (USACE, 2002b), but based on results from this study moderate to large floods will be able to bypass the structure and contribute large loads of sediment to the backwaters and maintain high sedimentation rates in the backwaters. Even with the protection of the high natural levee, sedimentation rates at JS Lake were nearly the same as at Hay Meadow Lake.

Dredging of the backwaters to create deep aquatic habitat has only provided a temporary solution to habitat loss. Dredge cuts fill in with sediment much more rapidly than undisturbed backwaters (Rogala and Boma, 1996) and the annual maintenance of the habitat rehabilitation project is costly. Sedimentation was observed to be widespread in Bertom and McCartney lakes after the 2001 flood (USACE, 2002b). It is not believed that further isolation of Hay Meadow Lake and JS Lake and/or dredging of the lakes will provide a long term, viable solution to the sedimentation problem occurring at these lakes.

5.2.6 Spatial Variability in Sedimentation and Grain Size

Backwater type (contiguous or isolated) and distance from the main channel have a major influence on the type of sediment deposited and the timing of sediment delivery.

The sediment delivered to JS Lake was generally coarser than the sediment delivered to Hay Meadow Lake. Even within JS Lake, JS-7 had a higher percentage of total sand and coarser sand than JS-9. Several other studies have shown similar patterns of deposition across the floodplain (Walling and He, 1998; Middelkoop and Asselman, 1998; Theis and Knox, 2003; Gomez *et al*., 1997). While coarser sediments fall out of suspension near the main channel during overbank floods, suspended sediments are carried across the floodplain and deposited in areas with slower currents.

Most backwaters with a hydraulic connection to the main channel of the UMR during low stages tend to accumulate fine sediments (Moody, 1997b; McHenry *et al*., 1984; Korschgen *et al*., 1987; Rogala *et al*., 1997). Coarse sediments drop out of suspension either before reaching the lakes or at the point where the channels flow into the still bodies of water (Korschgen *et al*., 1987; Eckblad *et al*., 1977). Hay Meadow Lake has accumulated silt sized sediment at HM-1 because distributary channels such as Crooked Slough are able to carry silt to the backwater even during lower stage flows. Flushing of the fine sediment during large floods occurs in many backwaters (Rogala and Boma, 1996; Rogala *et al*., 2003; Nakato, 1981a), but does not appear to a major factor at HM-1. The configuration of Hay Meadow Lake and its constriction at the downstream end by islands and the alluvial fan built by Dark Hollow Creek [fig. 6] likely cause water to slow down as it moves through the lake during flood events, thus limiting the potential for sediment resuspension and removal.

A greater understanding of the spatial variability of sedimentation within the individual backwaters and a greater understanding of the response of the contiguous backwater to individual floods is needed. Intensive coring and surveying of the backwaters could be undertaken to advance this understanding. The processes occurring within these backwaters may potentially have a large impact on the connected backwater lakes and habitats downstream.

5.3 June 2004 Summer Flood Results and Discussion

A detailed analysis of a small portion of the floodplain after the minor June 2004 flood was undertaken to examine sediment transport and depositional patterns during individual flood events. The site is characterized by a small swale, deciduous forest vegetation and a large log jam in the swale. Sedimentation within the study site was controlled by two main factors: local topography and a large woody debris dam. Graphs for each transect and surfaces based on the survey and lab analyses have been made. The transect graphs are found in Appendix B.

5.3.1 Local Topography

It has been suggested that moderate to large magnitude floods are responsible for the majority of overbank floodplain deposition (Knox, 2001; Knox and Daniels, 2002; Benedetti, 2003). While the entire floodplain was not affected by the 2004 flood, this study shows that relatively low magnitude, frequent floods do have the ability to transport moderately high quantities of sediment across the floodplain. Swales act as conduits during the smaller flood events (and large floods) and frequently deliver sediment to the backswamp areas of the floodplain and to the backwaters such as Hay Meadow Lake. Many low areas of the floodplain were inundated by the 2004 flood of 2.5-5 year recurrence (USACE, 2004), while several areas such as natural levees and nearby fields were elevated above the flood stage and did not experience deposition or erosion. Floodplain development during the smaller floods is clearly influenced by local relief and proximity to breaks in the natural levees.

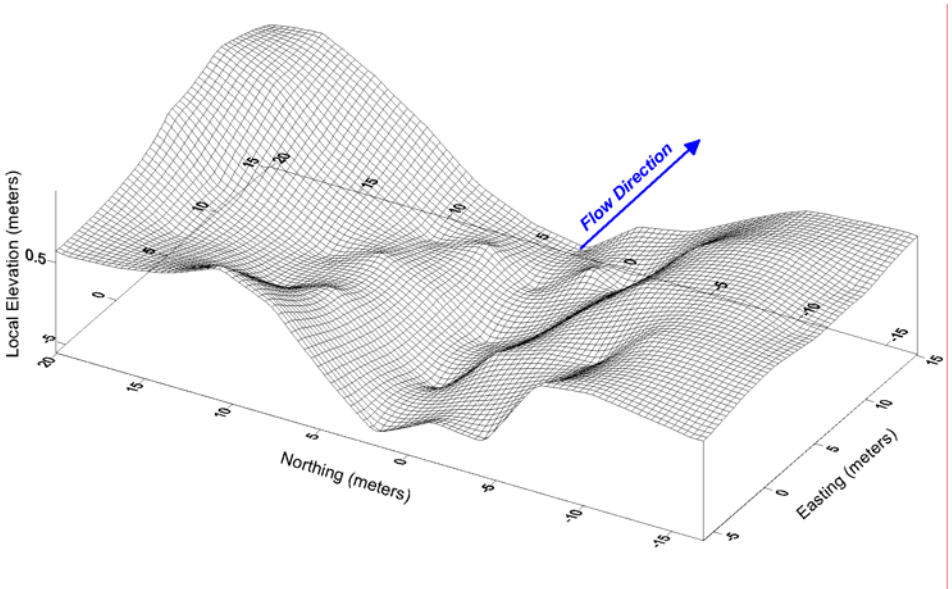
During the 2004 flood, an average of 13 mm of sediment was deposited at the study site, though much variability exists between the adjacent sampling points. Similar post-lock and dam sedimentation rates were found for Pools 9 and 10 (Benedetti, 2003; Knox, 2001).

As was shown with the post lock and dam rates in the backwater lakes, deposition associated with this 2.5-5 year flood (USACE, 2004) is an order of magnitude greater than the long-term trends observed at the floodplain sites in Pools 10 and 9 (Benedetti, 2003; Knox, 2001). The high rates of sedimentation associated with this study site may reflect the environmental characteristics of the local floodplain.

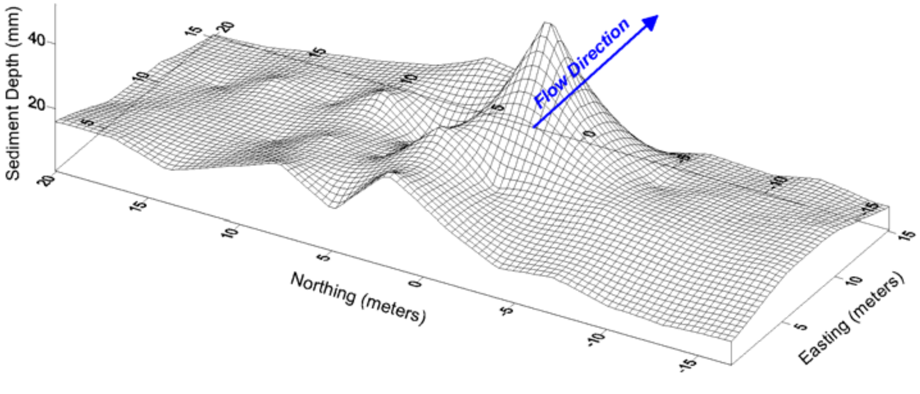
Figures 25-27, created from survey data and lab analyses of samples collected at the survey points show the patterns of sedimentation at the study site and provide insight into how the topography and debris dam have affected prior floods at the site. Trend lines have been created from these figures and show clear patterns in deposition.

Sedimentation generally increased with flood flow depth at the study site [fig. 25 and 28]. The maximum flood depth was approximately one meter as measured by a watermark on a tree in the swale. The maximum relief in the 36x21 meter study area is only 0.9 meters. During the flood, water was concentrated within the swale and flowed at high velocities. The concentration of flow combined with a longer inundation time caused greater deposition in the deeper areas. Sediment that was deposited within the deeper areas was generally coarser in texture than on the higher areas [fig. 26 and 29]. The concentration of water and higher velocities within the channel led to a higher transport capacity and ability to move coarse sediment. It was observed during the flood peak that fine and very fine sand were being transported and deposited by the overbank flow. After the flood, it was observed that higher areas within the study site only had a thin veneer of fine silty sediment deposited where flow had been shallower, slower, and vegetation cover greater.

While the floodplain had greater sediment accumulation in the swales during the 2004 flood, this pattern of deposition is not always the case. If low areas consistently experienced maximum deposition during floods, the floodplain would have little relief as the swales would be preferentially filled in. Large floods may scour sediment out of the swales as was seen in surveys of the Platte River System. During the 2000 flood, swales were scoured while maximum deposition occurred on the higher surfaces and in backwater flow separation zones (personal communication with J.C. Knox, 2005).

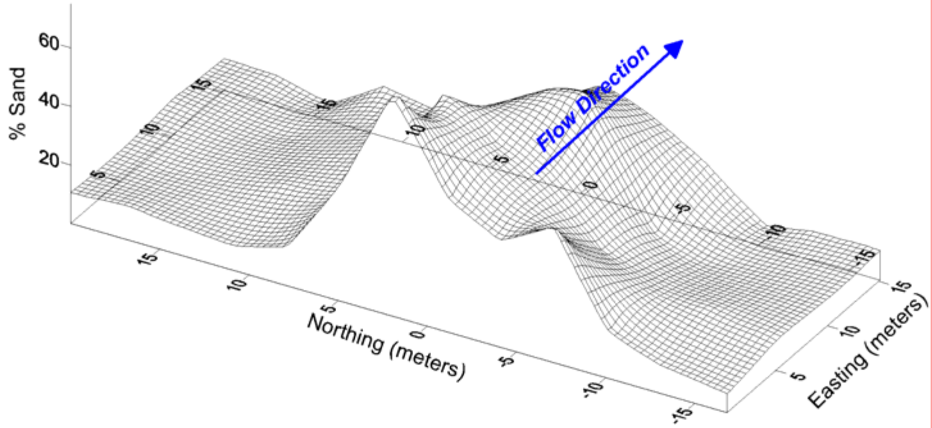


Local Elevation Grid for UMR Pool 11 Floodplain Study Area

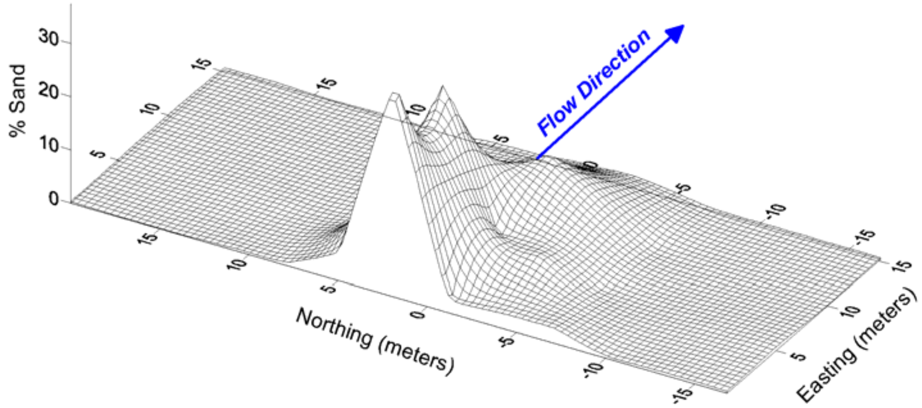


Average Estimated Depth of Sediment from the 2004 Early Summer Flood

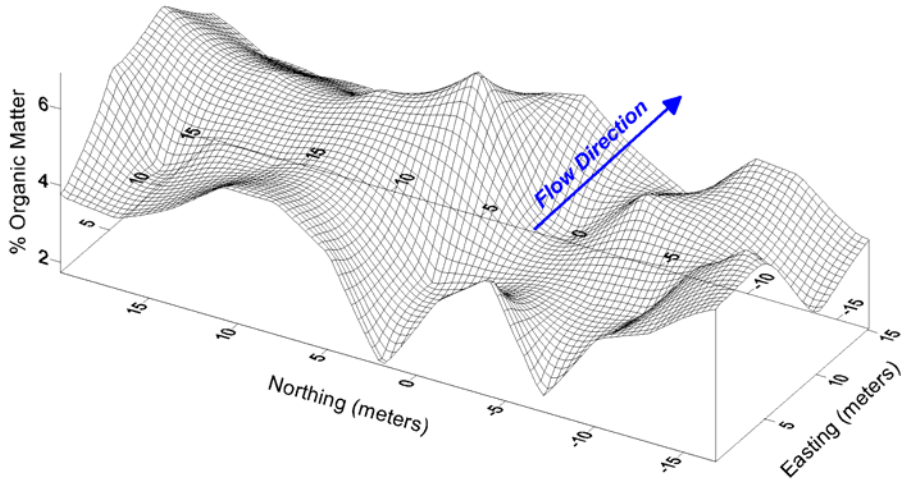
Figure 25. Local elevation and depth of sediment deposition recorded after the June of 2004 flood.



Percent Sand Deposited with the 2004 Early Summer Flood Sediment

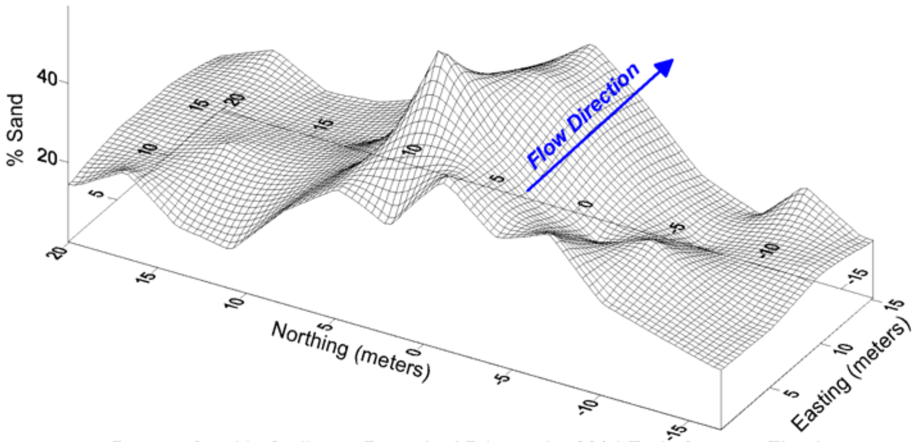


Percent Sand >= 0.250mm Deposited with the 2004 Early Summer Flood Sediment

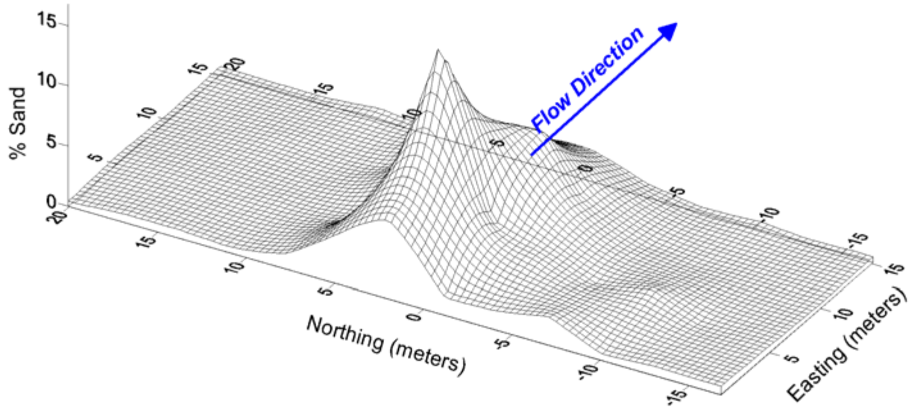


Percent Organic Matter in the 2004 Early Summer Flood Sediment

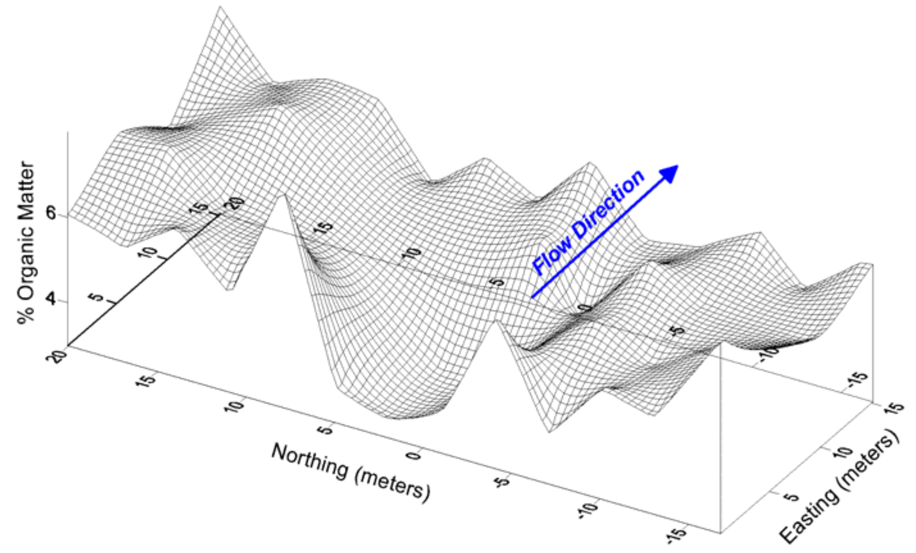
Figure 26. Analyses and patterns of the 2004 flood deposits.



Percent Sand in Sediment Deposited Prior to the 2004 Early Summer Flood



Percent Sand >= 0.250mm Deposited Prior to the 2004 Early Summer Flood



Percent Organic Matter in the Sediment Deposited Prior to the 2004 Early Summer Flood

Figure 27. Analyses and patterns of the pre-2004 flood surface sediment.

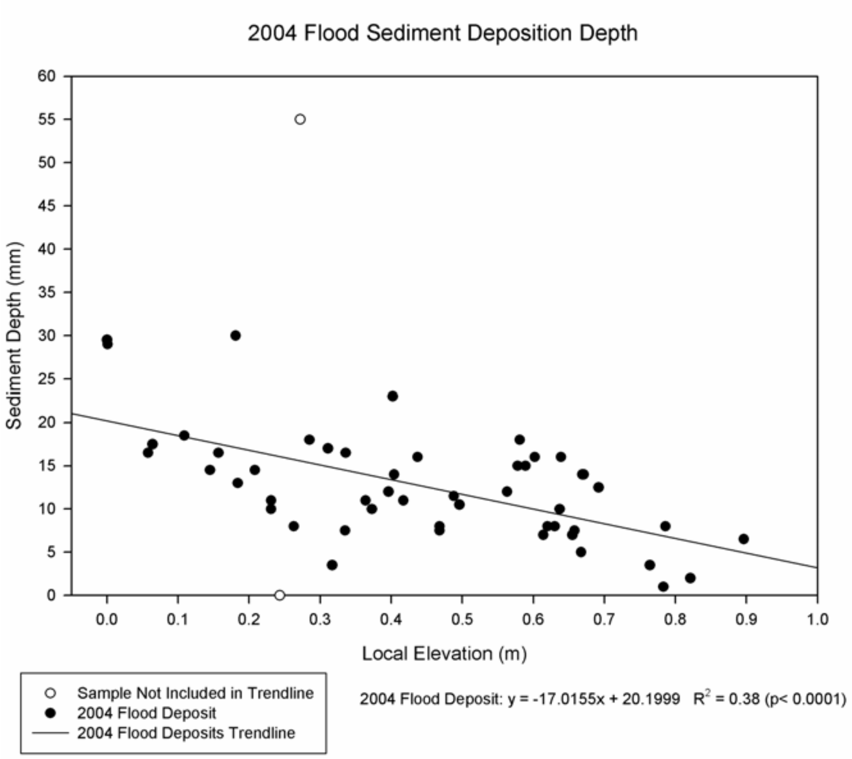


Figure 28. 2004 flood sediment deposition trend with depth.

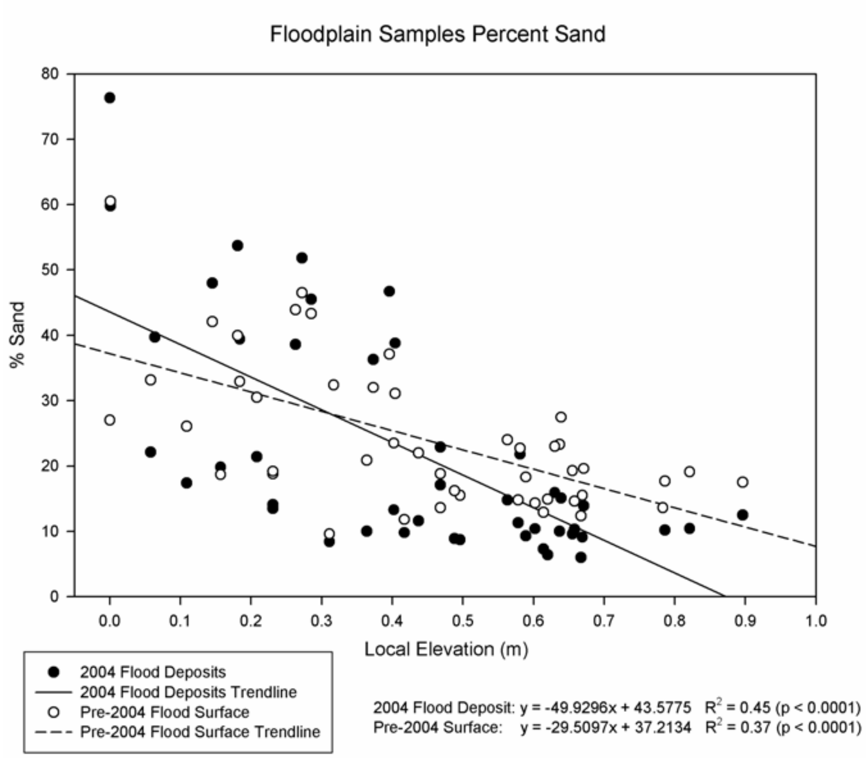


Figure 29. In both the 2004 flood deposits and the pre-2004 flood sediments, coarse sediment is found predominantly in the low areas while silt was found on the higher areas in the study site.

5.3.2 Large Woody Debris

Microtopography is the main influencing factor in the 2004 flood deposit thickness and grain size, yet flow obstructions such as log jams and tree trunks also influenced the depositional pattern. These floodplain features influence flow velocity, flow direction and inundation times. Several studies have documented a high degree of depositional variability across very small areas, mainly as a consequence of floodplain topography and large woody debris (Benedetti, 2003; Middelkoop and Asselman, 1998; Asselman and Middelkoop, 1995; He and Walling, 1998; Jeffries *et al*., 2003). The scatter in figures 28 and 29 is likely caused in large part by trees and a debris dam.

A 0.75 meter high log jam produced a major obstacle to flow as it moved through the one meter deep swale and across the floodplain [fig. 30]. Initially, as water flowed downstream in the swale, the coarsest sediments and the maximum amount of deposition were concentrated in the deepest areas of the survey site. With closer proximity to the debris dam flow began to be diverted around the obstruction. Immediately upstream of the debris dam, maximum deposition was still occurring behind the dam, likely as a result of ponding, but the sand fraction began to increase in the higher right bank of the swale. Immediately downstream of the dam deposition was greatest at the edge of the debris dam likely as a result of flow separation. After a distance of only 5-8 meters downstream of the debris dam maximum deposition was once again occurring in the deepest part of the swale.

Figure 30. The 0.75 meter high large woody debris dam influenced flow direction, velocity, and inundation during the June of 2004 flood and earlier floods.

While it is not surprising to see the effect this obstruction has on depositional patterns it nonetheless has important ramifications. The woody debris acts like a small-scale side channel closing structure. By analyzing the flow pattern around this structure it is evident that although sediment deposition occurs upstream of the log jam, flow diversion around the structure allows for the continued downstream transportation of sediment. It is not too unreasonable to think that similar flow and deposition patterns would occur during moderate to large floods around the larger partial side channel closing structures created by the U.S. Army Corps of Engineers in the slough entering Bertom Lake. A series of debris dams like the one reviewed in detail here are found across the active floodplain of the UMR. As was discussed in section 4.2.3 on the changes in the land cover at the study area, these log jams were not always present on the floodplain and their present day occurrence is an important component of sediment storage during flood events and may reduce the delivery of sediment to backwaters such as Hay Meadow Lake.

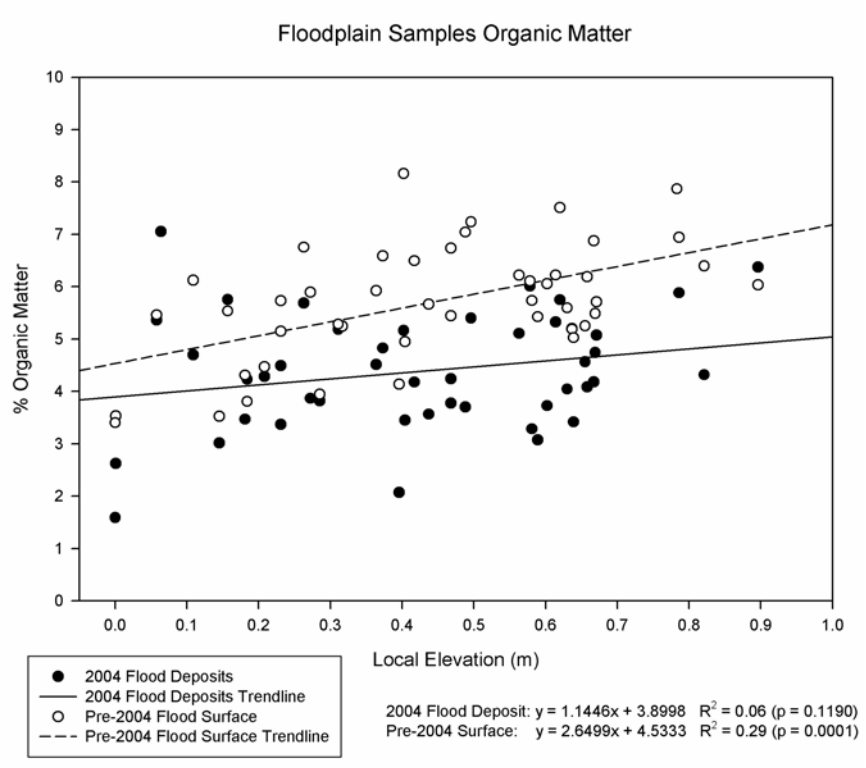


Figure 31. Percent organic matter has no statistically significant trend with elevation in the 2004 flood sediment, while it does tend to increase with elevation in the pre-2004 flood surface.

5.3.3 Organic Matter

No statistically significant trend in percent organic matter was found for the 2004 flood sediments, though deeper areas had slightly lower organic matter levels [fig. 26 and 31]. It is clear that the pre-2004 flood surface sediment had a higher percentage of organic matter than the 2004 flood deposits [fig. 31]. This finding is reasonable because enrichment of the pre-2004 surface with organic litter occurs between flood events. Similar findings of higher organic matter levels in sediments before floods than in freshly deposited sediments has been documented in the backwater lakes of this study and by others studying floodplain sedimentation (Benedetti, 2003; Theis and Knox, 2003). Lower elevations within the pre-2004 surface had lower percent organic matter than higher elevations [fig. 31]. The lower areas may have had organic matter removed during the 2004 flood and during earlier floods.

The growth of trees and vegetation in the channel is sparser and may also reduce the rate of accumulation of organic matter in the sediment.

5.3.4 Significance of Terrestrial Sedimentation

The evolution of the UMR floodplain is spatially complex. Topography and large woody debris have an important effect on sedimentation patterns. It has been shown that floodwater and sediment can be transported through the floodplain system during frequent, minor floods through floodplain swales. Though the entire floodplain may not experience deposition, fine sediment is delivered to the connected backwater areas during lower stage floods. While large magnitude floods are important in delivering large quantities of sediment to the entire floodplain, minor floods are also an important component of floodplain evolution and sediment delivery. An understanding of all the components of a floodplain is necessary when attempting to understand and possibly mitigate the loss of the backwater habitats.

An understanding of floodplain topography and sediment transport is also important when studying sedimentation at areas such as Hay Meadow Lake and JS Lake. These backwater lakes were once dry floodplain sites with topography not too different from the site studied in detail above. When estimating rates of sedimentation across inundated terrestrial floodplain areas like this, it is reasonable to expect a high degree of variability in the rates of sedimentation. Following lock and dam closure and the creation of backwater lakes, deeper swales inundated by the lakes likely filled in faster than the shallower areas and, if cored, would have higher rates of sedimentation than adjacent sites. The stratigraphy of cores might also vary over short distances depending on whether or not the core was taken from an area within a former swale that might have higher proportion of sandy sediment.

These issues should be taken into consideration when interpreting cores from flooded backwater sites.

Chapter 6 - Conclusions

While much research has been done on investigating sedimentation within backwaters of the upper Mississippi River, few studies have used a combination of methods to investigate the processes behind sedimentation. Most past studies only focused on how much was being deposited and not on how and when the deposition was occurring. This thesis has shown that with a detailed analysis of sediment cores taken from backwaters it is possible to gain a better understanding of sedimentation processes and variability in backwaters.

The combined use of particle size, organic matter, carbonate, and ^{137}Cs analyses in conjunction with river stage data provided a detailed record of post-lock and dam sedimentation at Hay Meadow Lake and JS Lake in Pool 11. One of the more surprising results from this study is how well percent dolomite and percent calcite trends corresponded with periods of large magnitude floods and infrequent small magnitude floods. While the use of ^{137}Cs has been prevalent in many studies of backwater sedimentation rates, this study has shown that when sampled at a coarse resolution it is truly only beneficial as a reconfirmation of results from other analyses. When using ^{137}Cs with a coarse sampling resolution the range of sedimentation rates at different time intervals is too large to provide comparable results.

The results from this study suggest that sedimentation rates are not as high as many other post-lock and dam studies have found. The contiguous backwater, Hay Meadow Lake, has experienced approximately 66 centimeters of sedimentation over the past 66 years at HM-1 for a sedimentation rate of 1.00 cm/yr or (1.35g/cm^2)/yr. The isolated backwater, JS Lake, had 55 centimeters of sedimentation near its center and 63 centimeters near its edge for a rate of 0.83-0.95 cm/yr from 1938-2003. Historical aerial photography interpretation shows that forest encroachment is not occurring at either of the backwaters, though homogenization of bed topography and loss of lake depth is a major concern in the lakes. Though the rate of sedimentation may not be as rapid as originally found for many UMR backwater lakes, the rates are still an order of magnitude above pre-settlement rates identified in Pools 9 and 10 (Knox, 2001; Benedetti, 2003). These backwaters likely do not provide the rich aquatic habitat for fish that they once did after closure of the locks and dams as a result of shallow conditions, low velocity flows and low dissolved oxygen levels during flat pool conditions.

Proximity to the source of sediment and connection to the main channel of the UMR are the major factors influencing the types and patterns of sedimentation at the backwaters. Sediments deposited at locations farther from the main channel were finer than those deposited near the main channel. Hay Meadow Lake, located farther from the main channel, had a slightly higher rate of deposition than JS Lake because water and fine sediment flowed to the lake throughout most of the year through a series of distributary channels. Sediment delivered to JS Lake came predominantly during large overbank floods.

Several backwaters in the UMR have high sedimentation rates from tributary streams draining into the backwaters and depositing their sediment loads. Sediment from local tributaries is not a major factor at either of the backwaters. The majority of the sediment delivered to both of the lakes comes from the UMR. Large floods have caused the greatest amount of sedimentation at both sites. The 2001, 1965, 1951 and 1952 floods were responsible for 81%, 58%, and 36% of the sedimentation at JS-7, JS-9 and HM-1 respectively. These results show that as long as large floods continue on the UMR, these sites will likely continue to experience high amounts of sedimentation. Attempts to reduce sediment delivery and provide aquatic habitat through means such as side channel closing structures and dredging will most likely not have a long-term significant effect on the delivery of sediment to the lakes or the availability of deep aquatic habitat.

Climate is the main driver behind the recent large floods on the UMR (Knox, 2003; Knapp, 1994). Knox (2003) has hypothesized that many of the recent large magnitude floods may be tied to global warming. If this is the case, the continuation of frequent large magnitude floods combined with remobilization of tributary sediment may maintain high sedimentation rates in the backwaters despite improvements in land use.

While large overbank floods contribute the majority of sediment to the floodplain, small floods still play an important role in floodplain evolution. Breaks in natural levees and floodplain depressions can deliver water and sediment to the floodplain during smaller magnitude floods. Contiguous backwaters can accumulate sediment during these smaller flood events in addition to the large flood events. Large woody debris also plays a role in sediment transport and floodplain storage. Floodplain depressions and debris dams may store sediment during smaller flood events and become a sediment source during larger floods. The influence of floodplain topography must be taken into account when analyzing cores collected from terrestrial or backwater floodplain sites. Significant variations in deposition occur over very short distances and may drastically influence estimated sedimentation rates and the interpretation of floodplain development.

Much insight has been gained on how these two backwaters vary in sedimentation processes and patterns, but there are many opportunities for continued research and understanding at this floodplain site. While it has been shown that the backwaters have become much shallower with time at the core sites, this may not be the case throughout the entire backwaters. Several studies have hypothesized that fine sediments are flushed out of backwaters during large magnitude floods. Though the sites cored in this study do not appear to show this pattern, it may occur at other locations within the lake. Pre and post-flood surveys of the lakes would clarify the extent of erosion occurring in the lakes during flood events. A more intensive survey of each lake was not feasible in this study, but a future study of how each backwater varies spatially by obtaining multiple cores across the backwaters would provide valuable information on flood scouring and differential rates of sedimentation within the backwaters.

An investigation of water chemistry, plant species and fish species at the sites would also be valuable. An analysis of water chemistry and sediment loads before, during and after floods as well as during peak photosynthesis in the lakes would provide insight into exactly how and when calcite and dolomite are deposited. If calcite is precipitated annually during peak photosynthesis, a higher resolution history of the lake sedimentation may be obtainable. Water chemistry, plant species, and fish species and diversity data for the lakes would provide greater evidence on the health of each backwater and the impact sedimentation has had on the biotic communities.

While the loss of the diverse backwater areas may seem inevitable, it is hoped that ongoing research in this area will continue to provide resource managers the information necessary to reduce sedimentation and habitat fragmentation. Continued efforts should be made to reduce upland erosion and sediment transport to the upper Mississippi River. While large floods may be responsible for the bulk of the backwater sedimentation, efforts can be made to reduce the quantity of sediment available for transport during the flood events.

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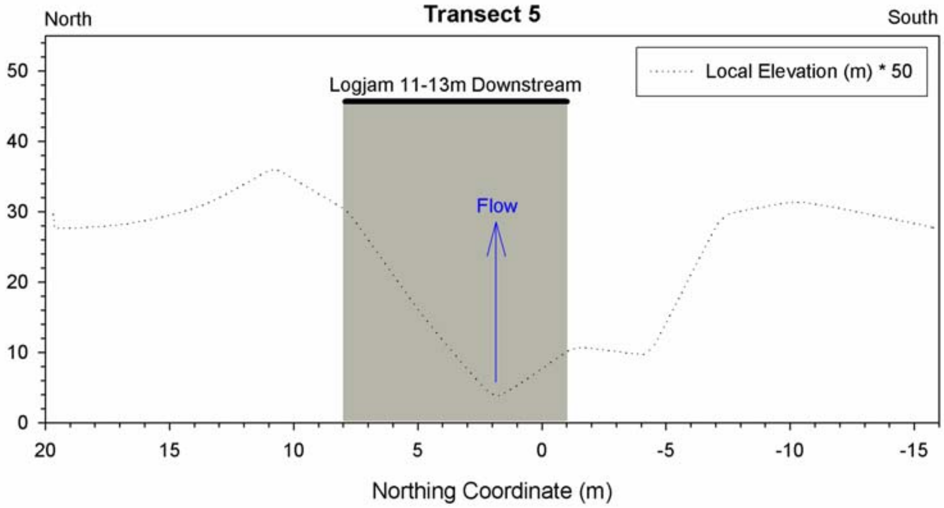
Appendix A – Bulk Density Analysis of HM-1

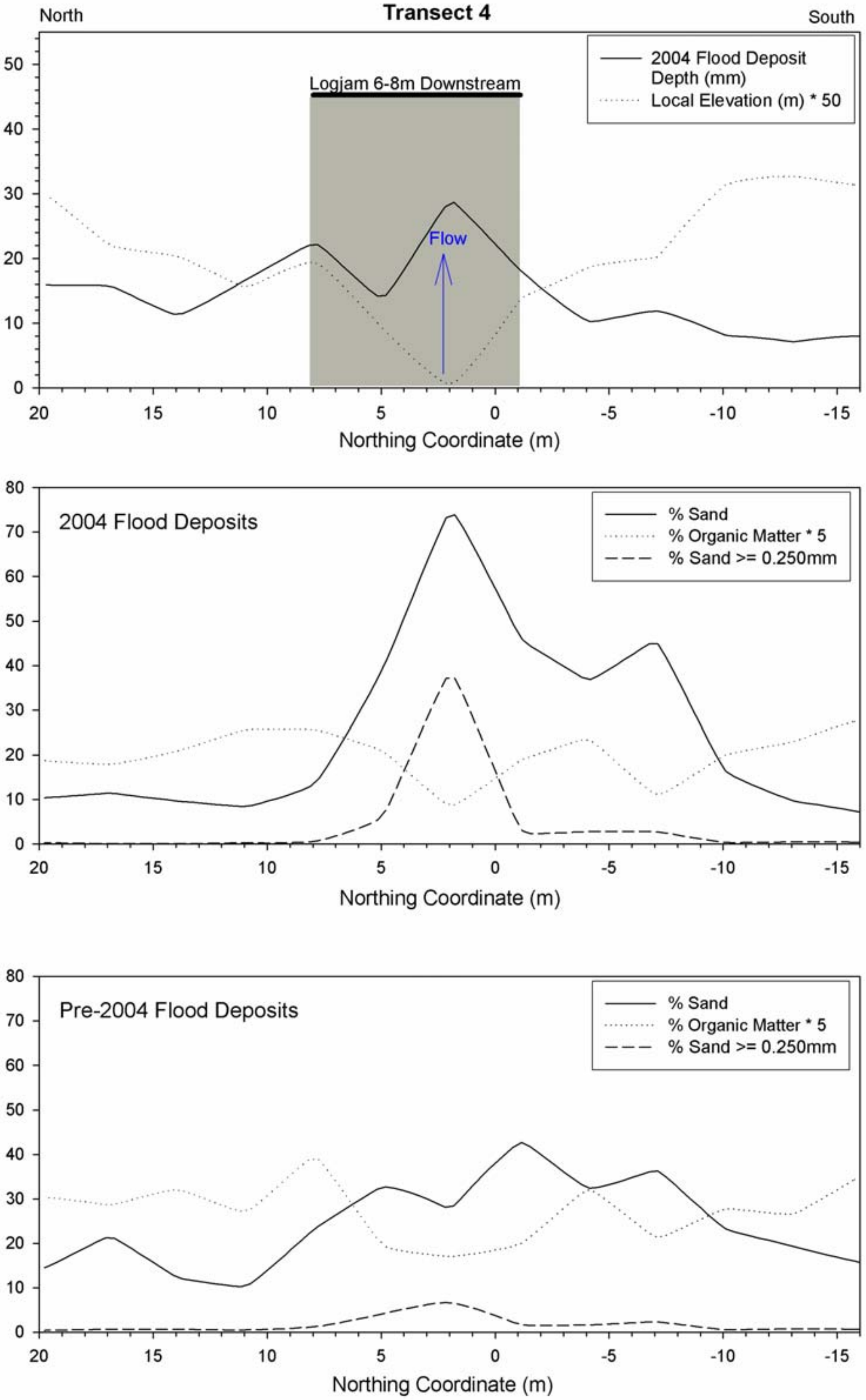
HM-1 Depth (cm)	Wet Bulk Density (g/cm^3)	Maximum* Wet Bulk Density Ratio Length (cm)	Minimum** Wet Bulk Density Ratio Length (cm)	Mean*** Wet Bulk Density Ratio Length (cm)
1	1.233	0.840	1.000	0.913
2	1.237	0.843	1.003	0.916
3	1.240	0.845	1.006	0.919
4	1.244	0.848	1.009	0.921
5	1.247	0.850	1.012	0.924
6	1.251	0.853	1.015	0.927
7	1.255	0.855	1.018	0.929
8	1.258	0.858	1.020	0.932
9	1.262	0.860	1.023	0.935
10	1.265	0.863	1.026	0.937
11	1.269	0.865	1.029	0.940
12	1.273	0.867	1.032	0.943
13	1.276	0.870	1.035	0.945
14	1.280	0.872	1.038	0.948
15	1.283	0.875	1.041	0.951
16	1.287	0.877	1.044	0.953
17	1.291	0.880	1.047	0.956
18	1.294	0.882	1.050	0.959
19	1.298	0.885	1.053	0.961
20	1.301	0.887	1.055	0.964
21	1.305	0.890	1.058	0.967
22	1.309	0.892	1.061	0.969
23	1.312	0.894	1.064	0.972
24	1.316	0.897	1.067	0.975
25	1.319	0.899	1.070	0.977
26	1.323	0.902	1.073	0.980
27	1.327	0.904	1.076	0.983
28	1.330	0.907	1.079	0.985
29	1.334	0.909	1.082	0.988
30	1.337	0.912	1.085	0.991
31	1.341	0.914	1.088	0.993
32	1.345	0.917	1.091	0.996
33	1.348	0.919	1.093	0.999
34	1.352	0.921	1.096	1.001
35	1.355	0.924	1.099	1.004
36	1.359	0.926	1.102	1.007
37	1.363	0.929	1.105	1.009
38	1.366	0.931	1.108	1.012
39	1.370	0.934	1.111	1.015
40	1.373	0.936	1.114	1.017
41	1.377	0.939	1.117	1.020
42	1.381	0.941	1.120	1.023

43	1.384	0.944	1.123	1.025
44	1.388	0.946	1.126	1.028
45	1.391	0.948	1.128	1.031
46	1.395	0.951	1.131	1.033
47	1.399	0.953	1.134	1.036
48	1.402	0.956	1.137	1.039
49	1.406	0.958	1.140	1.041
50	1.409	0.961	1.143	1.044
51	1.413	0.963	1.146	1.047
52	1.417	0.966	1.149	1.049
53	1.420	0.968	1.152	1.052
54	1.424	0.971	1.155	1.055
55	1.427	0.973	1.158	1.057
56	1.431	0.975	1.161	1.060
57	1.435	0.978	1.164	1.063
58	1.438	0.980	1.166	1.065
59	1.442	0.983	1.169	1.068
60	1.445	0.985	1.172	1.071
61	1.449	0.988	1.175	1.073
62	1.453	0.990	1.178	1.076
63	1.456	0.993	1.181	1.079
64	1.460	0.995	1.184	1.081
65	1.463	0.998	1.187	1.084
66	1.467	1.000	1.190	1.087

* Maximum Bulk Density	1.467 g/cm^3
** Minimum Bulk Density	1.233 g/cm^3
*** Mean Bulk Density	1.350 g/cm^3
Unadjusted Core Length	66.0 cm
Adjusted Maximum Core Length	72.3 cm
Adjusted Minimum Core Length	60.7 cm
Adjusted Mean Core Length	66.0 cm

Appendix B – Floodplain Survey Cross-Section Analyses




North
Transect 4
South
Logjam 6-8m Downstream
Flow
2004 Flood Deposit Depth (mm)
Local Elevation (m) * 50
0
10
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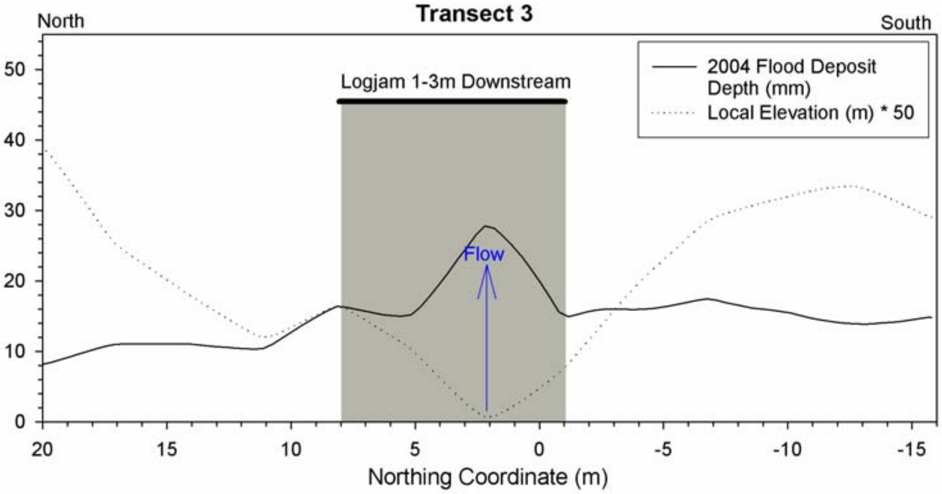
30
40
50
20
15
10
5
0
-5
-10
-15
Northing Coordinate (m)
2004 Flood Deposits
% Sand
% Organic Matter * 5
% Sand >= 0.250mm
0
10
20
30
40
50
60
70
80
Northing Coordinate (m)
Pre-2004 Flood Deposits
% Sand
% Organic Matter * 5
% Sand >= 0.250mm
Northing Coordinate (m)


Transect 3
North
South
Logjam 1-3m Downstream
Flow
2004 Flood Deposit Depth (mm)
Local Elevation (m) * 50
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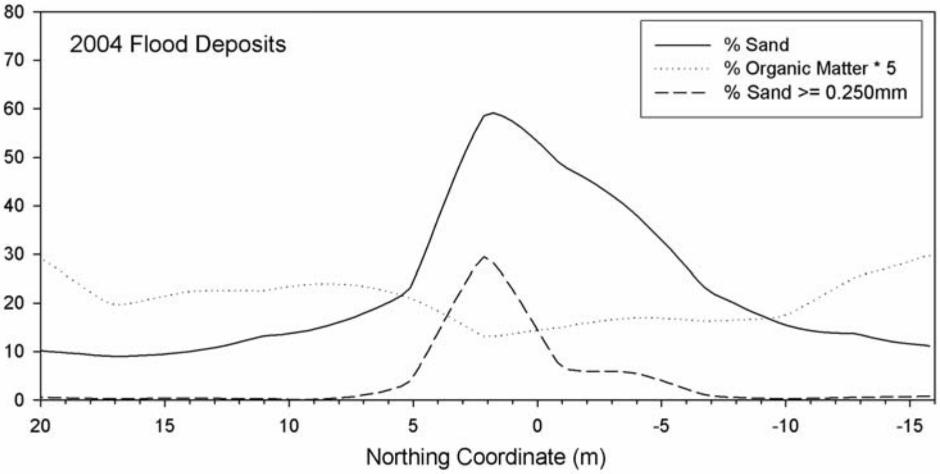
Northing Coordinate (m)


2004 Flood Deposits
% Sand
% Organic Matter * 5
% Sand >= 0.250mm
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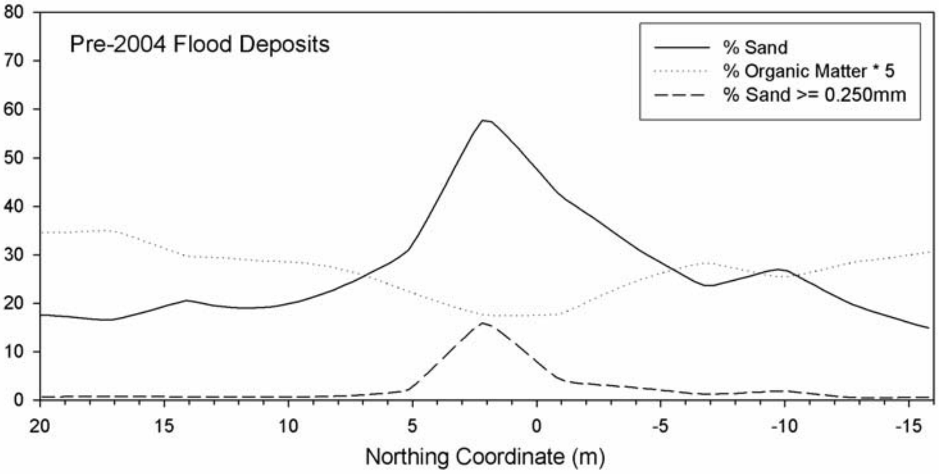
Northing Coordinate (m)


Pre-2004 Flood Deposits
% Sand
% Organic Matter * 5
% Sand >= 0.250mm
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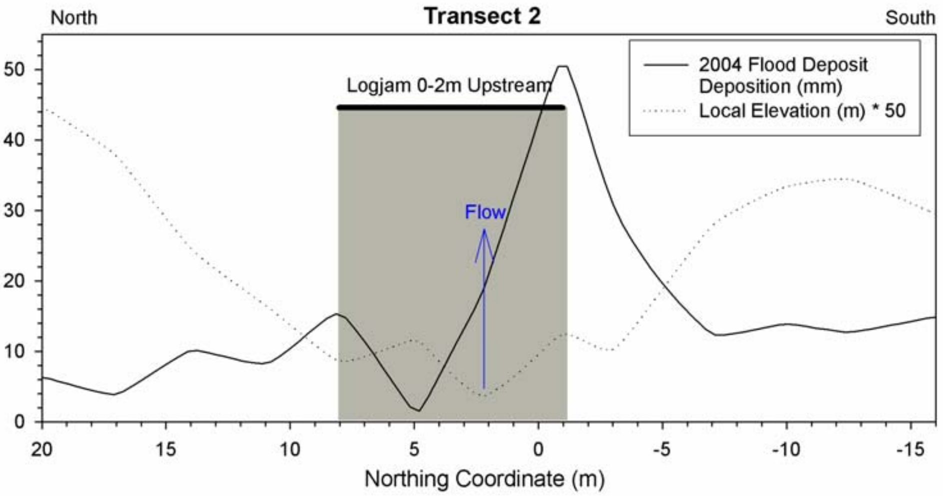
Northing Coordinate (m)


North
Transect 2
South
2004 Flood Deposit Deposition (mm)
Local Elevation (m) * 50
Logjam 0-2m Upstream
Flow
0
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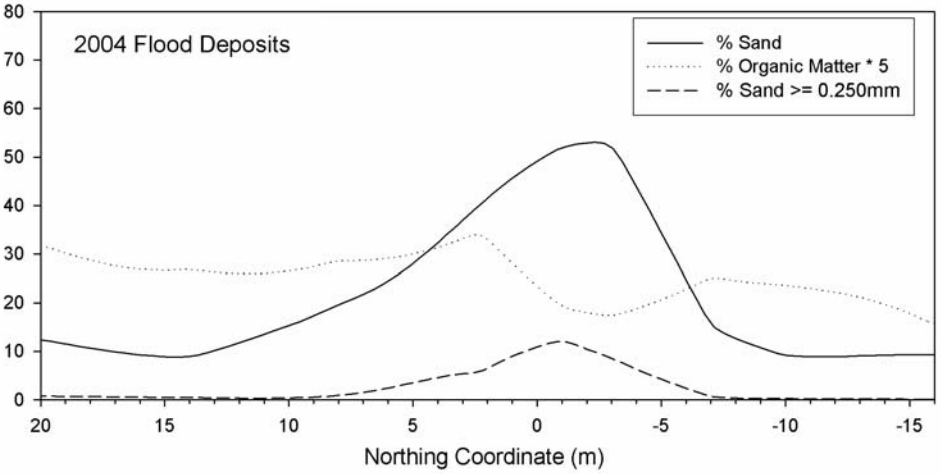
-10
-15
Northing Coordinate (m)


2004 Flood Deposits
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% Organic Matter * 5
% Sand >= 0.250mm
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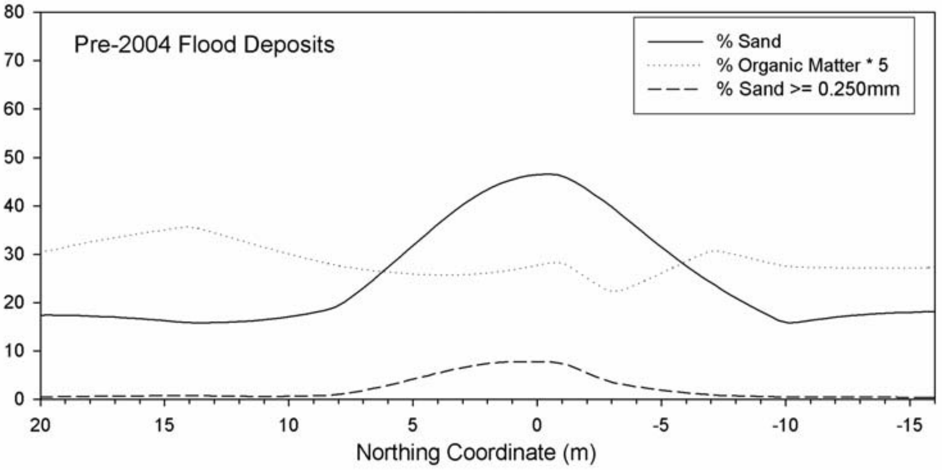
Northing Coordinate (m)


Pre-2004 Flood Deposits
% Sand
% Organic Matter * 5
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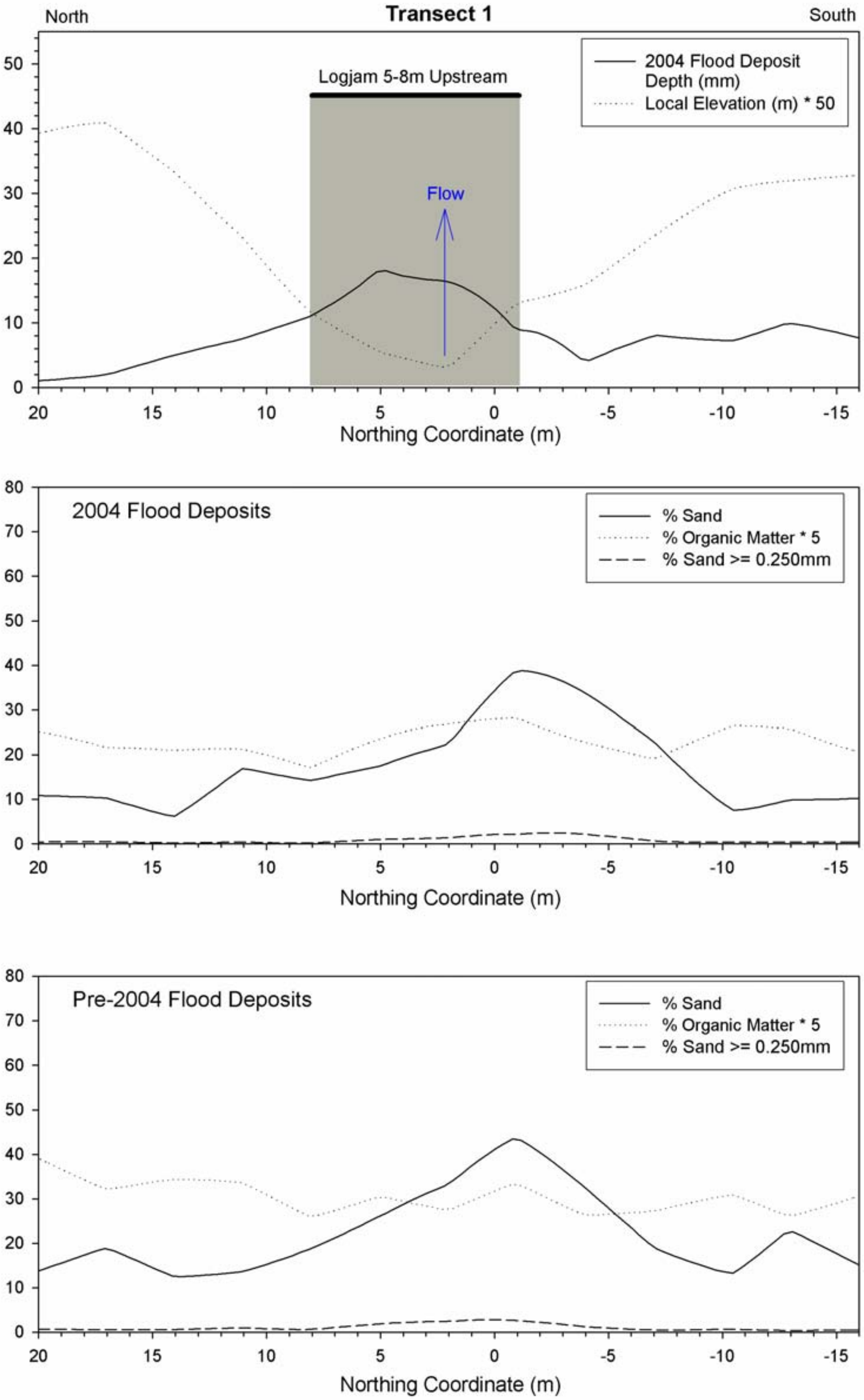
Northing Coordinate (m)


North
Transect 1
South
Logjam 5-8m Upstream
Flow
2004 Flood Deposit Depth (mm)
Local Elevation (m) * 50
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Northing Coordinate (m)
2004 Flood Deposits
% Sand
% Organic Matter * 5
% Sand >= 0.250mm
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Northing Coordinate (m)
Pre-2004 Flood Deposits
% Sand
% Organic Matter * 5
% Sand >= 0.250mm
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-15
Northing Coordinate (m)