ENV Report 40-1

FINAL REPORT

UPPER MISSISSIPPI RIVER
AND
ILLINOIS WATERWAY
CUMULATIVE EFFECTS STUDY

VOLUME 1:
GEOMORPHIC ASSESSMENT

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1 INTRODUCTION

1.1 BACKGROUND

Numerous and extensive modifications of the Upper Mississippi River (UMR) have been made by the Federal Government to allow safe and reliable navigation. Modifications to the UMR began as early as the 1830s. Congress authorized the construction of a 4 1/2-ft depth navigation channel in 1878. A deeper 6-ft depth navigation channel was authorized in 1907. The current 9-ft depth navigation channel was authorized in 1930 and largely constructed between 1930 and 1940. The 9-ft depth channel extends along the UMR from the confluence of the Ohio River upstream to Minneapolis, Minnesota and along the Illinois Waterway (IWW) from its confluence with the Mississippi River upstream to Lake Michigan. The involved navigation facilities are referred to as the 9-ft Channel Project.

This study seeks to quantify cumulative effects of activities related to the 9-foot navigation project on the environment and predict future conditions. Although direct impacts such as water impoundment, sedimentation, structures, and dredging are associated with the 9-ft Channel Project, it is important to understand that the cumulative effects along the UMR and IWW defined in this study are also the result of numerous other man-induced influences. These influences include the construction of numerous large reservoirs on tributaries, agricultural land-use practices, construction of levee systems for flood control and wildlife habitat, and possibly global climate change. Assessment of cumulative effects is therefore necessary to understand why and how the UMR and IWW has changed and to provide a basis to extrapolate future conditions.

1.2 STUDY AUTHORITY

The U.S. Army Corps of Engineers (USACE), Rock Island District, contracted WEST Consultants, Inc. (WEST) to prepare a cumulative effects analysis for the UMR and IWW under Contract No. DACW25-97-C-0012.

1.3 STUDY AREA

The study area encompasses the UMR and the IWW. The UMR extends from the confluence with the Ohio River near Cairo, Illinois upstream to approximately Minneapolis, Minnesota, a distance of about 850 river miles. The study area along the IWW extends from the confluence with the Mississippi River upstream to Lake Michigan, a distance of about 330 river miles. A location map for the study area is shown in Figure 1-1.

Figure 1-1: Study area location map.

1.4 OBJECTIVES

The general objective of the study is to assess the cumulative impacts of past, present, and reasonably foreseeable future actions associated with the continued operation of the 9-ft Channel Project on the UMR and IWW. Specifically, this study describes the cumulative effects of the existing 9-ft Channel Project on channel morphology and ecology. The study develops predictions of geomorphic and ecological conditions within the study area for the year 2050.

1.5 REPORT ORGANIZATION

The report is divided into two parts. In Volume 1, the cumulative effects on the geomorphic conditions of the UMR and IWW are evaluated. In Volume 2, an overview of the ecological effects, as measured by the responses of biota, to changes that have occurred since impoundment on the UMR and IWW is presented.

In addition to this introductory section, Volume 1 is comprised of the following nine chapters:

Chapter 2, DATA SOURCES, summarizes the sources of information relevant to the study. Select previous studies identified from the literature to be particularly relevant to the current work are reviewed.

Chapter 3, HYDROLOGIC CHARACTERISTICS, discusses the general hydrology of the Upper Mississippi River basin and describes cumulative effects on discharge and stage. Available research on global warming and its potential impacts on the hydrology and geomorphology of the UMR basin are reviewed.

Chapter 4, HYDRAULIC ANALYSIS, discusses the hydraulics of the system with emphasis on the portion of the system where hydraulic models are available.

Chapter 5, GEOMORPHIC ANALYSIS, discusses the geology and glacial history of the watershed, identifies the general watershed characteristics which influence or control channel morphology within the study area, and describes the history of human influences on the fluvial system including dredging. The characteristics of bed materials are described and estimates of sediment transport in the basin are presented. Historic plan form data are presented and analyses of changes are discussed. Finally, an evaluation of channel geometry is discussed, including comparisons of historic data for channel cross sections.

Chapter 6, SEDIMENT BUDGET, presents the methods and results of a sediment budget analysis for the Upper Mississippi River. Major sources and sinks of sediment through the study area are quantified and estimates of the historic rates of sediment transport between Pools 11 through 26 are made. The rate of sedimentation within backwater areas of the navigation pools is estimated.

Chapter 7, FUTURE GEOMORPHIC CONDITIONS, describes the procedures used to estimate future geomorphic and presents predictions of geomorphologic conditions for the year 2050.

Chapter 8, CONCLUSIONS AND RECOMMENDATIONS, describes the basic conclusions of the study and presents relevant recommendations.

Chapter 9, REFERENCES, lists the literature cited in Volume 1 of the report.

Volume 2 is comprised of the following four chapters:

Chapter 1, INTRODUCTION, discusses the motivation for the ecological assessment.

Chapter 2, APPROACH, describes the methods and approaches employed for the analysis.

Chapter 3, ASSESSMENT OF ECOLOGICAL EFFECTS OF HABITAT CHANGE AND OTHER HUMAN ACTIVITIES, discusses the changes in the system since the dams were installed to present. Predicted changes for the year 2050 are discussed.

Chapter 4, REFERENCES, lists the literature cited in Volume 2 of the report.

2 DATA SOURCES

2.1 DATA COLLECTION

A significant effort was made to identify, collate, and review existing literature for pertinent data and information. A major objective of the literature review was to identify existing data and corresponding feasible methods of analysis. The database of information resulting from this work effort is considerable and should be useful to any future environmental assessments of the Upper Mississippi River system. Primary sources of information considered in this study were provided by the Rock Island, St. Paul, and St. Louis Districts of the Army Corps of Engineers, the Environmental Management Technical Center (EMTC, U.S. Geological Survey (USGS)), Illinois Water Survey, and the Board of Consultants.

2.2 LITERATURE REVIEW

A large body of literature exists pertaining to the UMR basin. The literature consists of both localized studies of narrow issues and broad reviews of physical and ecological conditions pertinent to large portions of the system. A large number of studies were reviewed and analyzed for the present effort. To provide background for Volume 1 of the current study, the general results for several of the most significant studies are reviewed in this section. For other literature, the reader is referred to an annotated bibliography prepared by DeHaan (1998).

2.2.1 Upper Mississippi River

In the following paragraphs significant studies pertinent to the UMR are reviewed:

Simons et al. (1974) documented historic geomorphic changes through the Open River portion of the UMR. The study concludes that the position of the river has remained basically unchanged over the last 200 years and, in the absence of earthquakes or great floods, should remain so. Except for major secondary channels, natural side channels in the reach are being filled with sediment. Ultimately, most natural and man-induced side channels are expected to fill with sediment and become indistinguishable from the floodplain. Also, small secondary channels are expected to fill faster than large secondary channels. The report presents maps of the river bank lines for the years 1888 and 1968. The maps of historic bank lines are useful for the general identification of changes associated with main channel and secondary channel aquatic areas. Other aquatic areas cannot be distinguished from the maps.

Simons et al. (1975) examined the past and present geomorphic features of Pools 24, 25 and 26. The effects of several planned future development alternatives on river morphology were explored. They concluded that with unchanged operation of the pools the reach will remain essentially unchanged for the next 50 years.

McHenry and Ritchie (1975) investigated sedimentation rates in Pools 4 through 10 by measuring isotopes of nuclear testing fallout. A limited number of profiles were sampled in each pool. The sampled sites were selected in places where fine sediment deposition was expected. The study reports many areas in the pools where sedimentation rates are greater than 2.5 cm/year and in some cases larger than 5 cm/year.

Simons et al. (1976) explored geomorphic changes in Pool 4 since navigation became a significant factor within the system. Special attention is paid to the influences of tributaries on the Mississippi River. The influence of the construction of Lock and Dam 4 on the geomorphologic conditions of the river is discussed. Several alternatives to decrease sediment supply from the Chippewa River are presented.

Simons and Chen (1977) studied the Chippewa River and its impact on sedimentation and dredging in Mississippi River. Their main objective was to examine alternative measures to reduce dredging. They proposed several alternatives including installation of a sediment trap near the mouth of Chippewa River. It is noted that such a sediment trap was constructed in the early 1980s. The effect of the sediment trap is discussed later in the present report.

GREAT-I (1980) discusses sedimentation problems within a study reach extending from Minneapolis, Minnesota, to Guttenberg, Iowa. The study presents results of a comprehensive effort to measure the changes of the system from 1939 to 1973. It concludes that a significant decrease in open water area has occurred and recommends, among other things, that strong land erosion control should be initiated to prevent further losses.

Olson (1981) compared aerial photography from 1938 and 1973 to determine changes in floodplain areas. His study area included Pools 5 to 10 and the Minnesota River. He summarized changes for water areas and several categories of vegetation. Olson concluded that water area decreased for every pool, with the exception of Pool 10, over the study period.

Nakato (1981a) performed a sediment budget analysis for Pools 11 through 22 on the UMR. The data used in the analysis were very limited. No cross section data was available for Pool 13 and in most locations, available sediment measurement records were short. The sediment budget was initiated at Pool 19 and stops in Pool 22 in the downstream direction and in Pool 13 in the upstream direction. The sediment measurement station at Dubuque was used as a starting point for Pools 11 through 12. The author presents pool by pool estimates of sediment inputs and outputs, average sediment deposition, and dredging. The author warns against using the developed average deposition estimates to predict long-term deposition within the pools.

Hsu (1982) improved Nakato’s (1981) sediment budget by incorporating more data. Separate estimates are developed for deposition in the main channel and backwater areas. Overall, the results of the study are similar to those presented by Nakato (1981a).

McHenry et al. (1984) further reported on sedimentation rates in Pools 4 through 10. They found that the rate of sedimentation had decreased from 3.4 cm/year between 1954 and 1964 to 1.8 cm/year between 1965 and 1975. They concluded that the sedimentation rate is sufficient to convert backwater areas to marshes within 50 to 100 years. Hence, they suggest that soil conservation is very important to control sediment inputs to the river system.

Rose (1992) presented hydraulic and sediment data for three rivers: Chippewa River (near Caryville, at Durand, and near Pepin); at one site near Galesville on the Black River; and at one site at Muscoda on the Wisconsin River. The report provides relations between suspended sediment discharge, bedload discharge, total sediment discharge, and water discharge; a description of particle size characteristics of bed material, bedload and suspended load; and estimates of annual and average annual suspended load, bedload, and total sediment load for Water Years 1974 through1983.

Knox (1993) discusses a possible hydrologic response in the Upper Mississippi River Basin to global warming. The author argued that modest climate changes caused large and sometimes abrupt adjustments in both the magnitudes and frequencies of floods in the Upper Mississippi River valley. He concluded that global warming could significantly alter hydrologic conditions in the UMR basin.

Rogala and Boma (1996) investigated rates of sedimentation along selected backwater transects in Pools 4, 8, and 13 of the UMR. They surveyed several transects in each pool over the seven year time period of 1989 to 1996. They found large spatial and temporal variability in sedimentation between the transects. They report 0.25 cm/year as an average sedimentation rate for all the transects surveyed in the study. They note that this rate is considerably less than the rates reported by others. They attribute the difference to less bias in the selection of transects and a probable decrease in the rate of sedimentation. It is noted that the study reflects conditions for a relatively recent time period.

The U.S. Army Corps of Engineers, Rock Island District, prepared a comprehensive study of bank erosion along the UMR and IWW (USACE, 1997). Field survey trips were conducted in the fall of 1995 and covered reaches from RM 0 to RM 854 along the UMR and from RM 0 to RM 286 along the Illinois Waterway. Twenty-nine sites on the IWW and forty-three sites on the UMR were investigated. Detailed results for each site are presented in the report. The study concludes that about 20% of the IWW banks are severely eroded and approximately 14% of the UMR banks are actively eroding

The USGS EMTC prepared a summary report (EMTC, 1998) of data collected as part of its Long Term Resource Monitoring Program for the UMR. The report describes basic concepts in river ecology, describes the history of the basin, reviews general hydrologic and geomorphic conditions, and characterizes various flora and fauna in the river environment. The conditions along the IWW are described as an example of the impacts of human development on an aquatic system. The impacts of extreme flood conditions in the UMR basin are described by review of information associated with the great flood of

1993. The report concludes by presenting an ecological report card and forecasts of future conditions within each UMR floodplain reach. In Pools 1 through 13, sedimentation and erosion of islands in the impounded portion of each pool is indicated to be degrading habitat. Throughout Pools 14 through 26, suspended sediment loads and sedimentation problems are said to be increasing. Floodplain development is also said to have isolated half the floodplain. In the Open River segment of the UMR, much of the floodplain is described as being isolated from the river, the suspended sediment load is large, and water-level fluctuations are said to be extreme. The lower IWW is described as being in poor ecological condition. Limiting factors along the IWW are indicated to be sedimentation, altered water-level regimes, and contamination.

2.2.2 Illinois Waterway

In the following paragraphs significant studies pertinent to the IWW are reviewed:

Lee and Stall (1976) studied the sediment conditions in backwater lakes along the Illinois River. They state that if all sediment retained in the system would be spread over the floodplain the accumulation rate would be 0.48 cm/year (0.19 inches/year). The authors discuss estimated rates of sediment accumulation for several individual lakes along the river as well as the mechanics of sedimentation in individual lakes.

Bellrose et al. (1983) compared the physical conditions of bottomland lakes and the adjacent floodplain of the Illinois River valley in the early 1900s with present conditions and projected conditions for the early 21st century. Lake sedimentation rates for various time periods were estimated. The sedimentation rate of recent (1950s to 1970s) time periods were determined to be greater than the average rate for the total historic period (1903 to 1979). The number of years required for selected lakes to lose half their average depth under the various sedimentation regimes were estimated to range from 24 to 127 years. The annual rate of deposition in lakes was noted to lessen over time, as lakes become shallower.

Demissie and Bhowmik (1986) conducted an investigation of the sedimentation characteristics of Peoria Lake, which is the largest and deepest lake on the IWW. It is located between RM 162 and 182. Historic cross sections for 1903, 1965, 1976, and 1985 were compared at four locations. Since 1903, up to 14 feet of sediment accumulation could be observed in various locations of the lake. The navigation channel was noted to be relatively stable over the period of record. As of 1985, the lake was estimated to have lost up to 2/3 of its 1903 volume. The sedimentation rate of Peoria Lake was shown to be significantly larger compared to the sedimentation rates of other large reservoirs in Illinois. The trap efficiency was calculated to be decreasing between four different time periods between 1903 and 1985. The study concluded that if sedimentation continued at current rates, within 10 or 15 years the river and lake will reach dynamic equilibrium and net accumulation of sediment in the lake will be zero. Most of the area outside of the channel will become either a mud flat or a marshy wetland area depending on the ability of vegetation to grow in the lake sediments. However, it was noted that during floods, most of this area would be inundated.

Demissie et al. (1992) prepared an overall assessment of erosion and sedimentation in the IWW basin. A sediment budget for the IWW was prepared, which shows that on average 13.8 million tons of sediment is delivered to the IWW valley annually. The average annual outflow from the IWW valley at Valley City is 5.6 million tons. Therefore, about 8.2 million tons of sediment are deposited in the IWW valley each year. Major areas impacted by the sediment deposition are backwater lakes. An average capacity loss for the lakes of 72 percent was calculated. Sedimentation in the navigation channel is not considered as high as that in backwater lakes. The higher flow velocities and tow traffic in the channel are said to keep the sediment moving in the channel. Major problem areas are located downstream of the mouth of tributary streams that carry coarse sediment into the navigation channel. Areas of sedimentation are routinely dredged. The author also reviewed land use in the IWW watershed. About 80 percent of the basin is used for agriculture. Agricultural acreage increased significantly up to 1918. From 1918 to 1981, the rate of increase in acreage was moderate. The total acreage peaked in 1981 and decreased sharply in recent years. The acreage of grassy crops decreased from 20 million acres to 2 million acres over the period 1919 to 1987, while acreage of soybeans grew from zero to 8.5 million acres over the same period. Erosion rates associated with soybean farming are assumed greater than hay and other non-row crop farming. Increased mechanized farming methods and applications of fertilizers are also cited as potential agricultural land use factors relevant to erosion and sedimentation in the IWW. The authors conclude that without management of sediment, all the bottomland lakes along the IWW will eventually fill with sediment.

3 HYDROLOGIC CHARACTERISTICS

In this chapter, the hydrologic characteristics of the UMR basin are described. The climate, drainage area, general land use practices, and runoff patterns of the basin are characterized. The influence of flow regulation associated with the locks and dams of the 9-ft Channel Project is described. The potential implications of global warming on basin hydrology and future geomorphic conditions of the UMR are also discussed.

3.1 CLIMATE

The UMR basin has a sub-humid to humid continental climate. It is characterized by cold, dry winters and warm to hot, moist summers. Typically, the warm, moist air masses from the Gulf of Mexico alternate with cold air masses from Canada. Frequent and rapid changes in weather occur along associated fronts. Average annual precipitation in the basin varies from about 24 inches in the northwest to about 45 inches in the southeast. About three-quarters of total annual precipitation over the basin occurs between April and September. Typically, average monthly temperatures in the basin are lowest in January and highest in July.

3.2 DRAINAGE AREA

The UMR has a total drainage area of over 710,000 square miles at its confluence with the Ohio River. It includes major portions of five states (Illinois, Iowa, Minnesota, Missouri, and Wisconsin). The boundaries of the UMR basin and major tributaries are shown on Figure 1-1. The drainage areas of major tributaries to the UMR, which have water discharge and sediment transport measurement records, are listed in Table 3-1. As seen from the table, the drainage area of the UMR is dominated by the Missouri River downstream of RM 195.

Tributary drainage area to the UMR, between each lock and dam, that has no sediment transport record or estimate, is defined on Table 3-1 as ungaged drainage area. As seen from the table, Pool 4 has the greatest ungaged tributary area among all the pools along the UMR. A comparison of the accumulated gaged and ungaged tributary area along the UMR is shown in Figure 3-1. A maximum of about 20 percent of the total drainage area is ungaged along the UMR study reach. It is noted that in various pools, 100 percent of the tributary drainage area is ungaged. However, in each of these cases, the total ungaged drainage area is very small compared to the total drainage area of the UMR at the same location.

Table 3-1: Tributary drainage areas to the Upper Mississippi River.

River Mile	Pool	Station/Tributary/Location	Gage No.	Drainage Area (sq. mi.)	Percent Ungaged D.A. in Pool
865		Mississippi River at Anoka, MN	05288500	19,100	
854.1		St Anthony Falls L&D		19,680	
847.7	1	Ungaged Tributary Area		4	100.00%
847.7	1	L&D No. 1		19,684	
844	2	Minnesota River at Mankato, MN	05330000	16,200	
815.2	2	Ungaged Tributary Area		1,106	6.39%
815.2	2	L&D No. 2		36,990	
811.3	3	St. Croix R. at St. Croix Falls, WI	05340500	6,240	
796.9	3	Ungaged Tributary Area		1,940	23.72%
796.9	3	L&D No. 3		45,170	
763.4	4	Chippewa River near Pepin, WI		9,010	
752.8	4	Ungaged Tributary Area		2,920	24.48%
752.8	4	L&D No. 4		57,100	
750.2	5	Zumbro River at Kellog, MN	05374900	1,400	
744	5	Whitewater River near Beaver, MN	05376800	271	
738.1	5	Ungaged Tributary Area		74	4.24%
738.1	5	L&D No. 5		58,845	
728.3	5A	Ungaged Tributary Area		260	100.00%
728.3	5A	L&D No. 5A		59,105	
725.7	6	Ungaged Tributary Area		95	100.00%
725.7	6	Mississippi River at Winona, MN	05378500	59,200	
714.2	6	Ungaged Tributary Area		830	100.00%
714.2	6	L&D No. 6		60,030	
710	7	Black River near Galesville, WI	05382000	2,080	
702.5	7	Ungaged Tributary Area		230	9.96%
702.5	7	L&D No. 7		62,340	
693.7	8	Root River near Houston, MN	05385000	1,270	
679.1	8	Ungaged Tributary Area		1,160	47.74%
679.1	8	L&D No. 8		64,770	
671	9	Upper Iowa near Dorchester, IA	05388250	770	
647.9	9	Ungaged Tributary Area		1,070	58.15%
647.9	9	L&D No. 9		66,610	
634.8	10	Ungaged Tributary Area		890	100.00%
634.8	10	Mississippi River at McGregor, IA	05389500	67,500	
630.7	10	Wisconsin River at Muscoda, WI	05407000	10,400	
615.1	10	Ungaged Tributary Area		1,700	14.05%
615.1	10	L&D No. 10		79,600	
608.1	11	Turkey River at Garber, IA	05412500	1,545	
593	11	Grant River at Burton, WI	05413500	267	
588.5	11	Platte River near Rockville, WI	05414000	142	
586.4	11	Little Maquoketa R. at Durango, IA	05414500	130	
583	11	Ungaged Tributary Area		416	16.64%
583	11	L&D No. 11		82,100	
579.3	12	Mississippi R. at East Dubuque, IL		82,100	
564.8	12	Galena River at Buncombe, WI	05415000	125	
556.7	12	Ungaged Tributary Area		275	68.75%
556.7	12	L&D No. 12		82,500	
548.6	13	Maquoketa R. near Maquoketa, IA	05418500	1,553	
545.1	13	Apple River near Hanover, IL	05419000	247	
536.5	13	Plum River below Carrol Creek, IL	05420000	230	
522.5	13	Ungaged Tributary Area		1,070	34.52%
522.5	13	L&D No. 13		85,600	
506.5	14	Wapsipinicon R. near DeWitt, IA	05422000	2,330	
493.3	14	Ungaged Tributary Area		470	16.79%
493.3	14	L&D No. 14		88,400	
482.9	15	Ungaged Tributary Area		100	100.00%
482.9	15	L&D No. 15		88,500	

River Mile	Pool	Station/Tributary/Location	Gage No.	Drainage Area (sq. mi.)	Percent Ungaged D.A. in Pool
479	16	Rock River near Joslin, IL	05446500	9,549	
479	16	Green River near Geneseo, IL	05447500	1,003	
457.2	16	Ungaged Tributary Area		448	4.07%
457.2	16	L&D No. 16		99,500	
437.1	17	Ungaged Tributary Area		100	100.00%
437.1	17	L&D No. 17		99,600	
434	18	Iowa River at Wapello, IA	05465500	12,500	
431.3	18	Edwards River near New Boston, IL	05466500	445	
427.5	18	Pope Creek near Keithsburg, IL	05467000	183	
410.5	18	Ungaged Tributary Area		872	6.23%
410.5	18	L&D No. 18		113,600	
409.9	19	Henderson Creek near Oquawka, IL	05469000	432	
404.1	19	Ungaged Tributary Area		0	0.00%
404.1	19	Mississippi River at Burlington, IA	05469720	114,032	
396	19	Skunk River at Augusta, IA	05474000	4,303	
364.2	19	Ungaged Tributary Area		665	13.39%
364.2	19	L&D No. 19		119,000	
363.9	20	Mississippi River at Keokuk, IA	05474500	119,000	
361.4	20	Des Moines R. at St. Francisville, MO	05490600	14,330	
353.6	20	Fox River at Wayland, MO	05495000	400	
343.2	20	Ungaged Tributary Area		570	3.73%
343.2	20	L&D No. 20		134,300	
341	21	Bear Creek near Marcelline, IL	05495500	349	
337.3	21	Wyaconda River above Canton, MO	05496000	393	
324.9	21	Ungaged Tributary Area		158	17.56%
324.9	21	L&D No. 21		135,200	
323	22	North Fabius R. at Monticello, MO	05497000	452	
323	22	Middle Fabius R. near Monticello, MO	05498000	393	
323	22	South Fabius R. near Taylor, MO	05500000	620	
321	22	North River at Palmyra, MO	05501000	373	
301.2	22	Ungaged Tributary Area		462	20.09%
301.2	22	L&D No. 22		137,500	
301.2	22	Mississippi River at Hannibal, MO		137,500	
284.1	24	Salt River near New London, MO	05508000	2,480	
273.4	24	Ungaged Tributary Area		920	27.06%
273.4	24	L&D No. 24		140,900	
241.5	25	Ungaged Tributary Area		1,100	100.00%
241.5	25	L&D No. 25		142,000	
217.5	26	Illinois River at Valley City, IL	05586100	26,744	
217.5	26	Mississippi River below Grafton, IL	05587455	171,300	
202.9	26	Ungaged Tributary Area		200	100.00%
202.9	26	L&D No. 26		171,500	
202.9	OR	Mississippi River at Alton, IL	05587500	171,500	
195	OR	Missouri River		525,500	
180	OR	Ungaged Tributary Area		0	0.00%
180	OR	Mississippi River at St. Louis, MO	07010000	697,000	
161	OR	Meramec River near Eureka, MO	07019000	3,788	
117.6	OR	Kaskaskia River near Venedy, IL	05594100	4,393	
109.9	OR	Ungaged Tributary Area		3,419	29.47%
109.9	OR	Mississippi River at Chester, IL	07020500	708,600	
75.6	OR	Big Muddy R. at Murphysboro, IL	05599500	2,169	
43.7	OR	Ungaged Tributary Area		2,431	52.85%
43.7	OR	Mississippi R. at Thebes, IL	07022000	713,200	
0	OR	Ohio River			

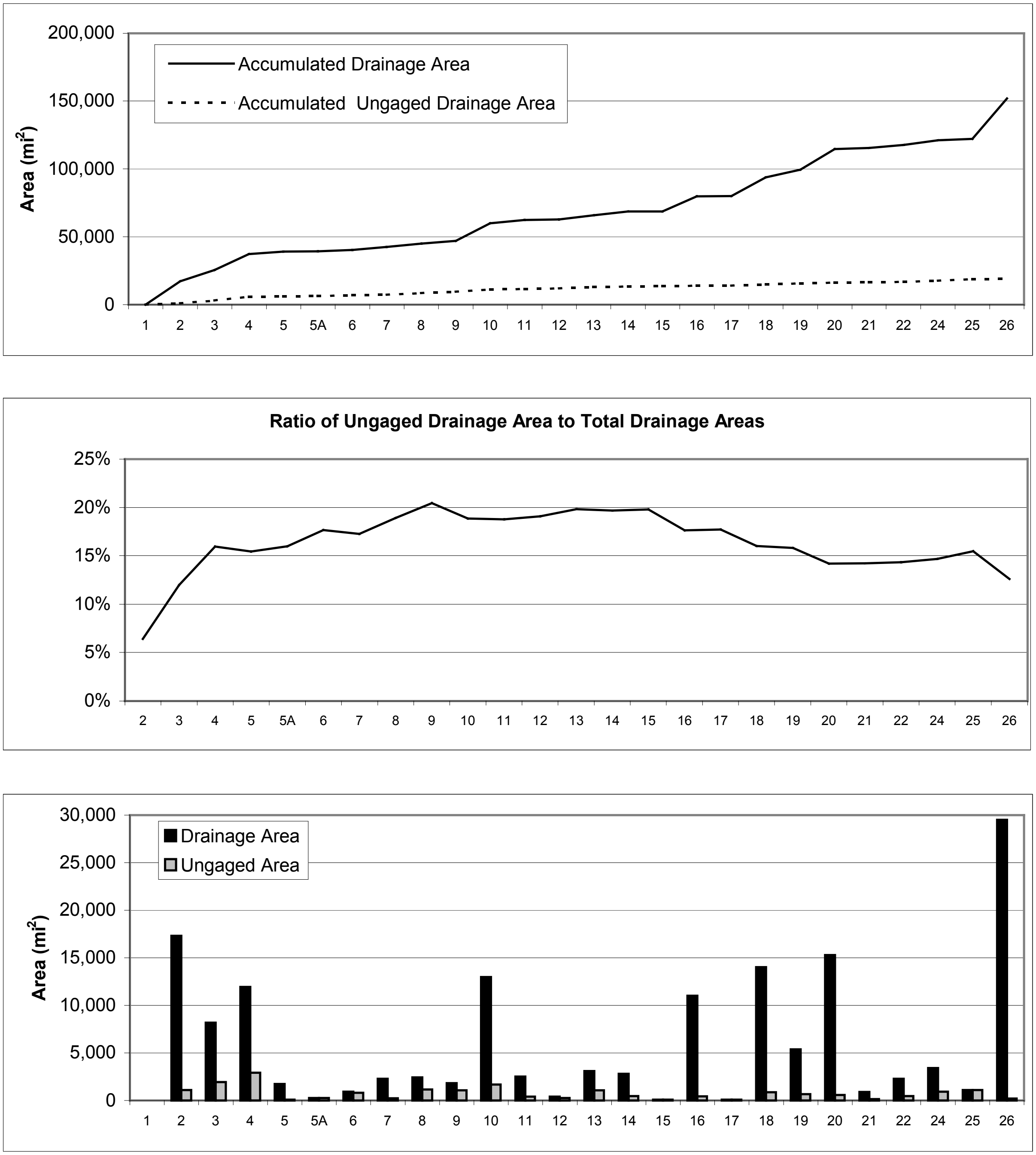


Figure 3-1: Comparison of total drainage area to ungaged drainage area for Pools 1 through 26 of the UMR.

3.3 LAND COVER / LAND USE

The distribution of major land cover and land use for the year 1992 in the states comprising the majority of the UMR basin is shown in Figure 3-2. Cropland is the primary land use in Iowa (70 percent), Illinois (67 percent), Minnesota (39 percent) and Missouri (30 percent). Forestland is the primary land use in Wisconsin (38 percent) and a significant portion of the land use in Minnesota (26 percent) and Missouri (26 percent). Pastureland makes up almost 27 percent of land use in Missouri but is 10 percent or less in the other UMR basin states. The "Other" land use category shown in the figure represents urban areas, transportation-related land areas, and water areas.

Various land use changes have occurred since construction of the 9-ft Channel Project in the 1930s. Significant watershed land use differences include changed cropping patterns, improved agricultural practices, and construction of numerous reservoirs on tributaries. In general, these changes have substantially reduced watershed sediment supplies to the UMR. Various researchers have attributed a reduction of upland soil erosion to changing agricultural practices since the 1950s (Knox and Hudson, 1995; Argabright et al., 1996). As shown in Table 3-2, estimates of historic sheet and rill erosion for agricultural lands in UMR basin states indicate a decreasing trend for watershed sediment supply. Furthermore, as discussed in Section 5.3, historic suspended sediment measurements for various UMR tributaries show significant decreases over the period of record.

An analysis of historic land use patterns was conducted by Demissie et al. (1992) to understand erosion and sedimentation rates within the IWW basin. The analysis concentrated on agricultural land use since it comprises almost 80 percent (cropland and pastureland) of State of Illinois land area. Statewide agricultural land use changes were evaluated. It is assumed that the results of the study are representative of historic agricultural land use changes in the other states of the UMR basin. Conclusions of the study include the following:

Table 3-2: Average annual sheet and rill erosion estimates for various land uses in states tributary to the UMR (NRCS, 1994).

State	Year	Cultivated (tons/acre)	Noncultivated (tons/acre)	Total (tons/acre)	Pastureland (tons/acre)	Rangeland (tons/acre)
Illinois	1982	6.4	2.8	6.3	1.6	0
	1987	5.3	2.9	5.2	1.3	0
	1992	4.4	2.1	4.3	1.0	0
Iowa	1982	7.8	3.2	7.5	1.4	0
	1987	6.5	4.0	6.3	1.5	0
	1992	5.6	2.0	5.4	1.3	0
Minnesota	1982	2.6	1.1	2.4	0.3	0
	1987	2.6	1.0	2.5	0.3	0
	1992	2.4	0.7	2.2	0.3	0
Missouri	1982	10.9	1.4	9.6	2.0	2.8
	1987	8.5	1.3	7.5	1.7	2.7
	1992	6.7	1.0	5.5	1.7	3.1
Wisconsin	1982	5.2	2.3	4.2	0.6	0
	1987	4.6	2.7	3.8	0.6	0
	1992	4.1	1.6	3.2	0.6	0

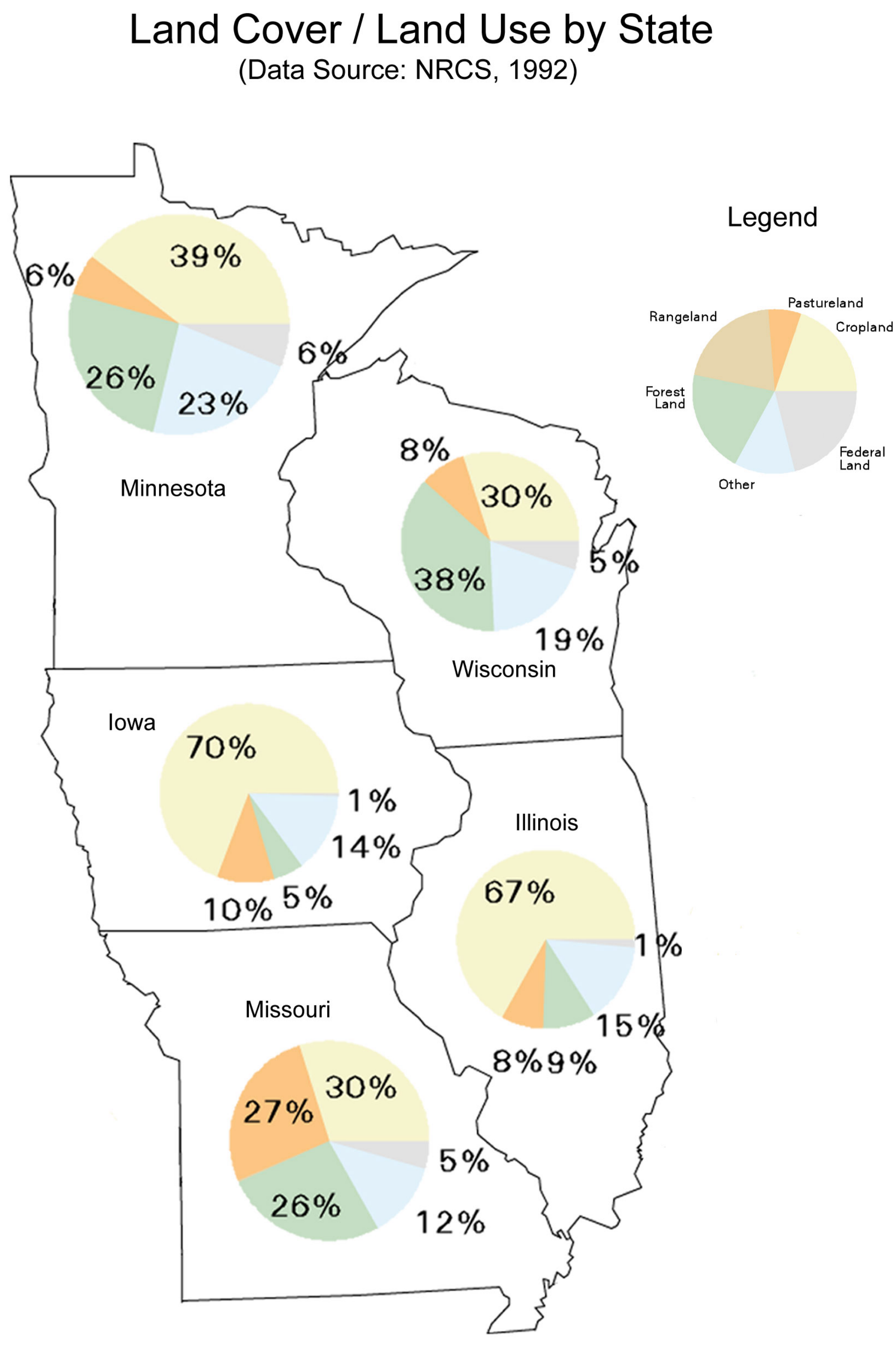


Figure 3-2: Distribution of land use among states in UMR basin. Federal land can range from forest land to parking lots and buildings.

- Total agricultural acreage increased significantly from initial land settlement until 1918. From 1918 to 1987, the rate of increase was moderate. The expansion of agriculture increased watershed erosion and sediment yield. However, increased agricultural acreage over 70 years (from 1925 to 1989) does not appear to be a major factor for increased watershed erosion and sedimentation.

- As seen in Figure 3-3, the acreage of land planted to wheat, oats, and hay declined over the period 1925 to 1987. A proportional increase occurred in the acreage of soybeans. Soybean farming is assumed to be associated with a higher soil erosion rate compared to farming of non-row crop agricultural land uses.

- Increased erosion rates from cropland may be associated with advances in farm technology and increased use of fertilizers. Improved tractors and plowing technology loosen cropland soils more completely, making them more erodible. The use of fertilizers allows farming of marginal areas, increasing areas of higher erosion potential.

The Demissie et al. (1992) study demonstrates that modern agriculture introduces certain factors that enhance erosion potential. However, as is shown in Table 3-2, improved land use practices counteract these influences, leading to a net decrease in watershed erosion.

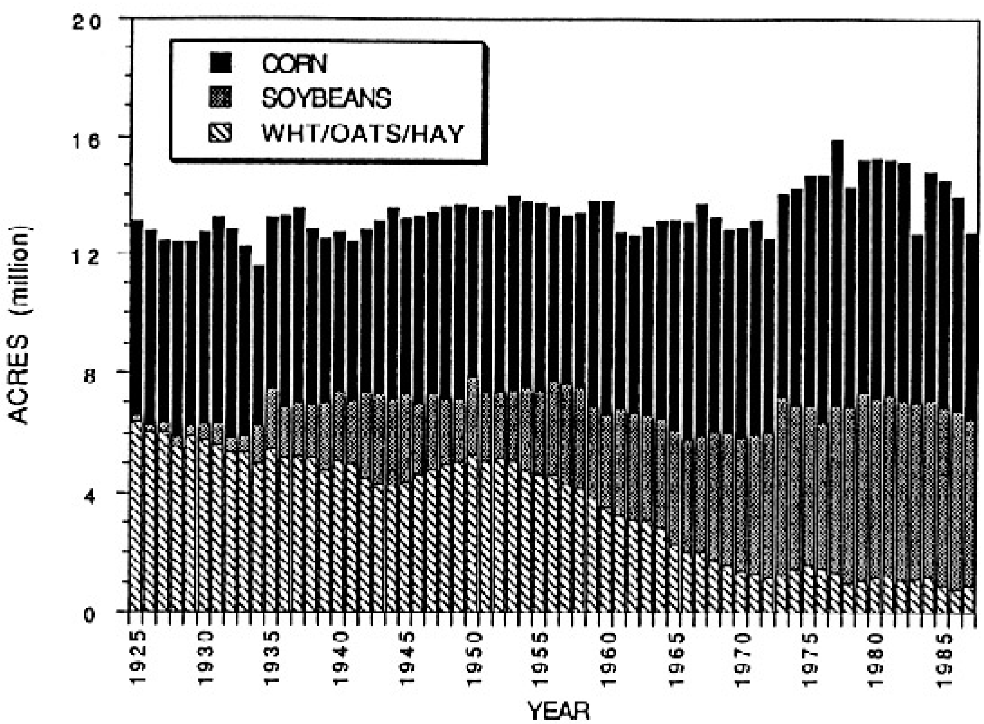


Figure 3-3: Historic acreage of major crops in Illinois (from Demissie et al, 1992).

3.4 RUNOFF

The majority of surface water runoff in the UMR is supplied by precipitation within the basin. Minor contributions of flow are made by municipal and industrial water sources such as diversions from Lake Michigan and aquifers (USACE, 1994). The average annual precipitation over the basin is 31.7 inches. An estimated 24.2 inches is lost to evapotranspiration. Approximately 7.5 inches of runoff passes out of the basin along the UMR. The distribution of runoff within the basin is shown Figure 3-4.

The runoff pattern in the UMR is similar throughout the basin. Although floods can occur during any month of the year along the UMR, nearly 75 percent are concentrated during the months of March through July (Knox, 1988). Floods along the UMR most commonly occur as a result of snowmelt or a combination of rainfall and snowmelt. Low flows typically occur between late summer and mid-winter. In winter months, recharge can be limited by the storage of moisture as snow and ice and reduced infiltration caused by frozen ground.

In the mid-upper Mississippi River valley at Keokuk, Iowa, data collected by the USGS for the period 1873 through 1997, show that flows range from a maximum average daily discharge of about 97,000 cfs in April to a minimum average daily discharge of about 33,500 cfs in January. Upstream, at St. Paul, Minnesota, USGS data for the period 1892 through 1997 indicate that flows range from a maximum average daily discharge of about 25,300 cfs in April to a minimum average daily discharge of about 4,500 cfs in February. The lowest flow corresponds with the winter when a large part of the middle and upper watershed either has frozen ground or is snow covered.

A summary of average annual flow rates for major tributaries to the UMR is shown in Table 3-3. The largest tributary and average annual flow contribution to the UMR is the Missouri River. However, as seen in the table, the size of tributary drainage area can not accurately predict the average annual flow. Runoff in the basin is related to the distribution of precipitation and for the majority of the basin generally increases in a northwest to southeast direction. The average annual flow of the Minnesota River and Iowa River, which drain the northwest portion of the watershed are substantially smaller than the average annual flow of other smaller tributaries which drain eastern portions of the basin.

3.5 FLOW REGULATION

The locks and dams of the UMR 9-ft Channel Project are operated for a single purpose: navigation. During low to moderate runoff periods, water flow is regulated by the UMR locks and dams to maintain required navigation depth. The water control regime of UMR dams may also be modified to achieve environmental benefits or mitigate adverse environmental impacts, when such modifications do not adversely impact the navigation objective. For example, management of pool water level has been used for environmental benefit. The Flood Control Act of 1944 made recreation an authorized project purpose. Lockage of recreational watercraft is routinely conducted as an integral part of the navigation mission.

Stage regulation caused by locks & dams is not the only influence on the flow characteristics of the UMR. The discharge and stage of flow is affected by numerous other man-made and natural influences. These influences include levees, wing dams, bridges, channel erosion and sedimentation, dredging, dams and reservoirs on major tributaries, watershed land use, consumptive water use, and even climate change (EMTC, 1998; Simons et al, 1974). The cumulative hydrologic impacts of these influences may be reflected as changes in the total flow volume; maximum, average, or minimum discharge; maximum, average, or minimum stage, and pattern of discharge and stage along the UMR.

3.5.1 Upper Mississippi River Discharge Records

Measurements of discharge have been made at various locations along the UMR since the mid to late 19th century. Examination of the discharge records provides information on man-induced and natural influences on the flow characteristics of the river. In the following paragraphs, the flow records of four locations along the UMR are examined.

3.5.1.1 Average Daily Discharges: January and July.

Long-term discharge records for the UMR at St. Paul, Minnesota, Clinton, Iowa, and Keokuk, Iowa are shown in Figure 3-5 and Figure 3-6. The figures depict the maximum and minimum average daily discharge for the months of January and July throughout the period of record. The graphs have not been plotted at a common size; therefore, it is important to consider the absolute range of discharge at each station when making comparisons. Although flows for all months were examined, only graphs for January and July are presented here for brevity.

Inspection of Figure 3-5 and Figure 3-6 indicate an apparent trend toward increasing magnitudes of runoff during the winter. The January maximum and minimum flows at St. Paul, Minnesota (Pool 2) have experienced both a strong general upward trend in flow magnitudes and increased variability during the last 30 to 40 years. July maximum and minimum flows at St. Paul seem to be little affected. The maximum and minimum flows for the downstream gages at Clinton, Iowa (10.6 miles downstream of Lock and Dam 13) and at Keokuk, Iowa (at Lock and Dam 19) show very weak upward trends for January maximum flows, but somewhat stronger upward trends in January minimum flows. Maximum and minimum discharges during July at the Clinton and Keokuk gages show little evidence for trends, as was the situation at the St. Paul gage.

UMR Basin - Average Annual Runoff
1951 - 1980

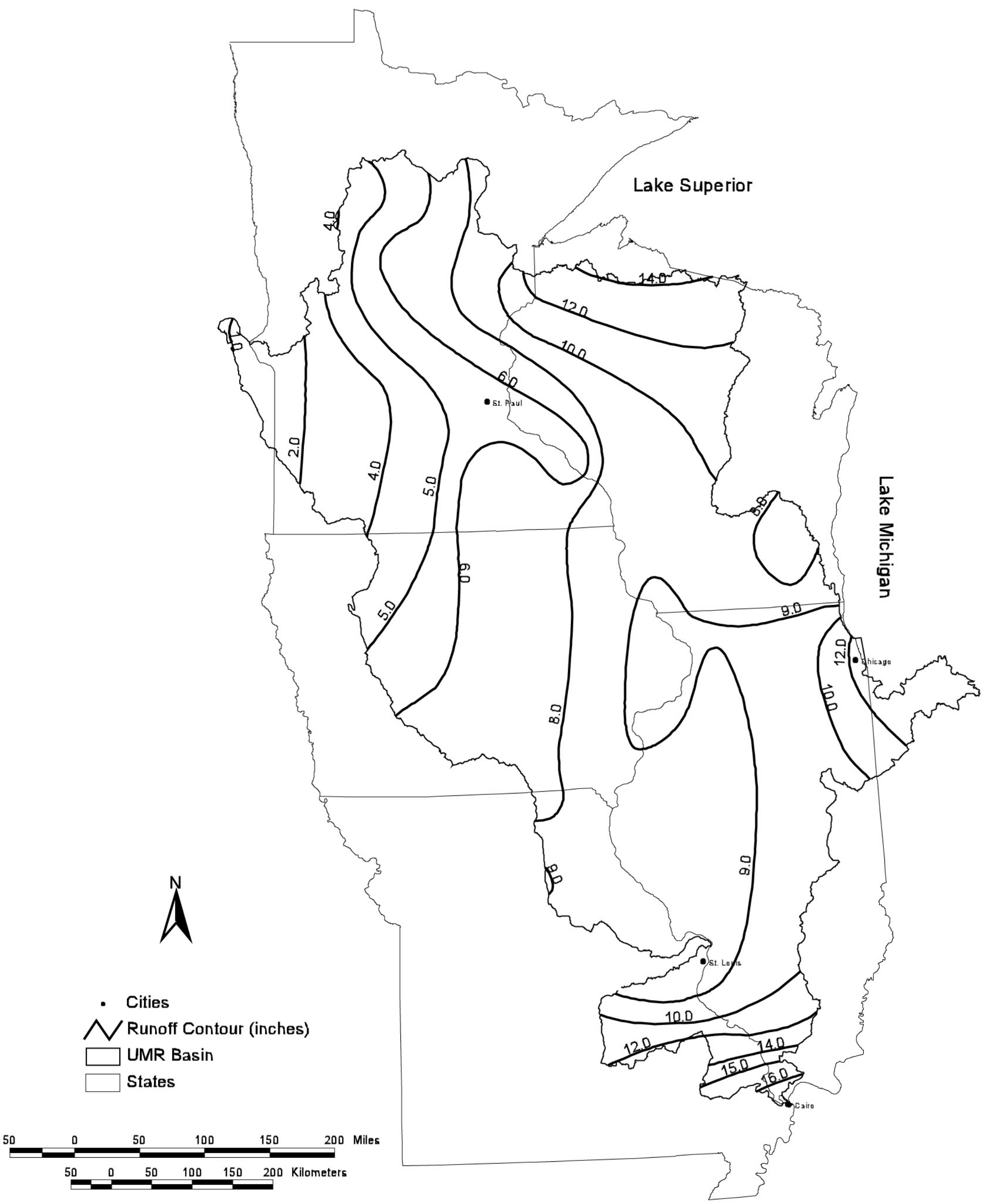


Figure 3-4: Average annual runoff in the UMR basin (USGS, 1998).

Table 3-3: Average annual flow along major tributaries to the UMR.

Tributary	Gage No.	Drainage Area (sq. mi.)	Average Annual Flow (cfs)
Galena River at Buncombe, WI	05415000	125	78
Little Maquoketa R. at Durango, IA	05414500	130	85
Platte River near Rockville, WI	05414000	142	101
Pope Creek near Keithsburg, IL	05467000	183	116
Plum River below Carrol Creek, IL	05420000	230	147
Whitewater River near Beaver, MN	05376800	271	168
Grant River at Burton, WI	05413500	267	169
Apple River near Hanover, IL	05419000	247	179
Bear Creek near Marcelline, IL	05495500	349	228
Wyaconda River above Canton, MO	05496000	393	258
Fox River at Wayland, MO	05495000	400	261
North River at Palmyra, MO	05501000	373	264
Middle Fabius R. near Monticello, MO	05498000	393	273
North Fabius R. at Monticello, MO	05497000	452	289
Henderson Creek near Oquawka, IL	05469000	432	290
Edwards River near New Boston, IL	05466500	445	294
South Fabius R. Near Taylor, MO	05500000	620	407
Upper Iowa near Dorchester, IA	05388250	770	629
Green River near Geneseo, IL	05447500	1,003	641
Root River near Houston, MN	05385000	1,270	719
Zumbro River at Kellog, MN	05374900	1,400	880
Turkey River at Garber, IA	05412500	1,545	986
Maquoketa R. near Maquoketa, IA	05418500	1,553	1,050
Wapsipinicon R. near DeWitt, IA	05422000	2,330	1,624
Salt River near New London, MO	05508000	2,480	1,739
Black River near Galesville, WI	05382000	2,080	1,778
Big Muddy R. at Murphysboro, IL	05599500	2,169	1,881
Skunk River at Augusta, IA	05474000	4,303	2,550
Meramec River near Eureka, MO	07019000	3,788	3,227
Kaskaskia River near Venedy, IL	05594100	4,393	3,784
Minnesota River at Mankato, MN	05330000	16,200	4,058
St. Croix R. at St. Croix Falls, WI	05340500	6,240	4,301
Rock River near Joslin, IL	05446500	9,549	6,332
Iowa River at Wapello, IA	05465500	12,500	7,431
Chippewa River at Durand, WI	05369500	9,010	7,672
Wisconsin River at Muscoda, WI	05407000	10,400	8,742
Des Moines R. at St. Francisville, MO	05490600	14,330	10,567
Illinois River at Valley City, IL	05586100	26,744	27,016
Missouri River at Herman, MO	06934500	524,200	78,883

3.5.1.2 Annual Minimum Daily Average Discharges

The annual maximum and minimum daily average discharges at St. Paul, Minnesota, Clinton, Iowa, and Keokuk, Iowa are shown in Figure 3-7. The St. Paul, Clinton, and Keokuk gage records each show a clear upward trend in magnitude of the annual minimum discharge. In general, this trend begins in the early 1940s. Although the specific effect of water storage reservoirs in the watershed on minimum discharges is unknown, it is likely substantial.

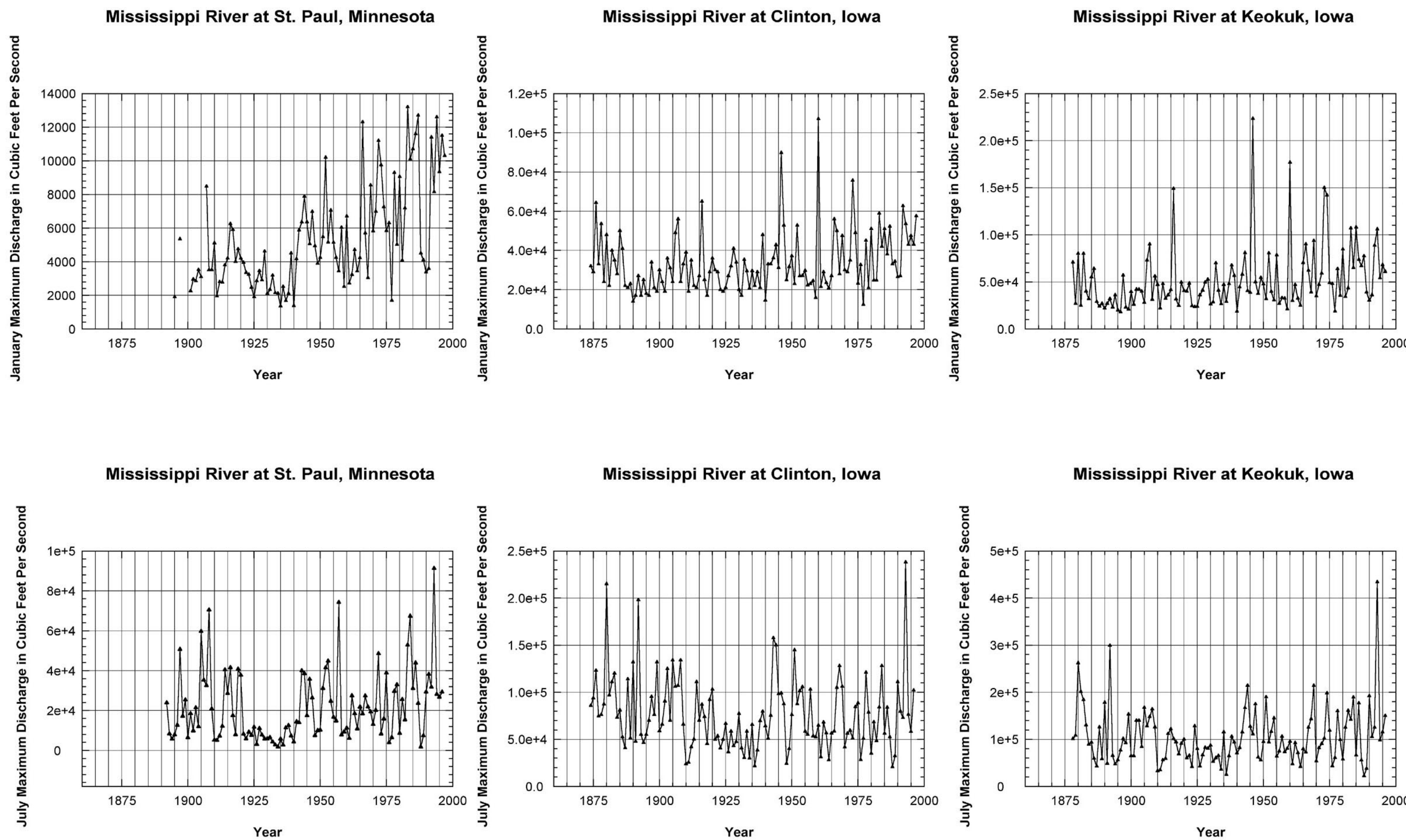


Figure 3-5: Maximum average daily discharge for January and July at three Upper Mississippi River U.S. Geological Survey gaging sites. (Note: ordinate scale changes between plots).

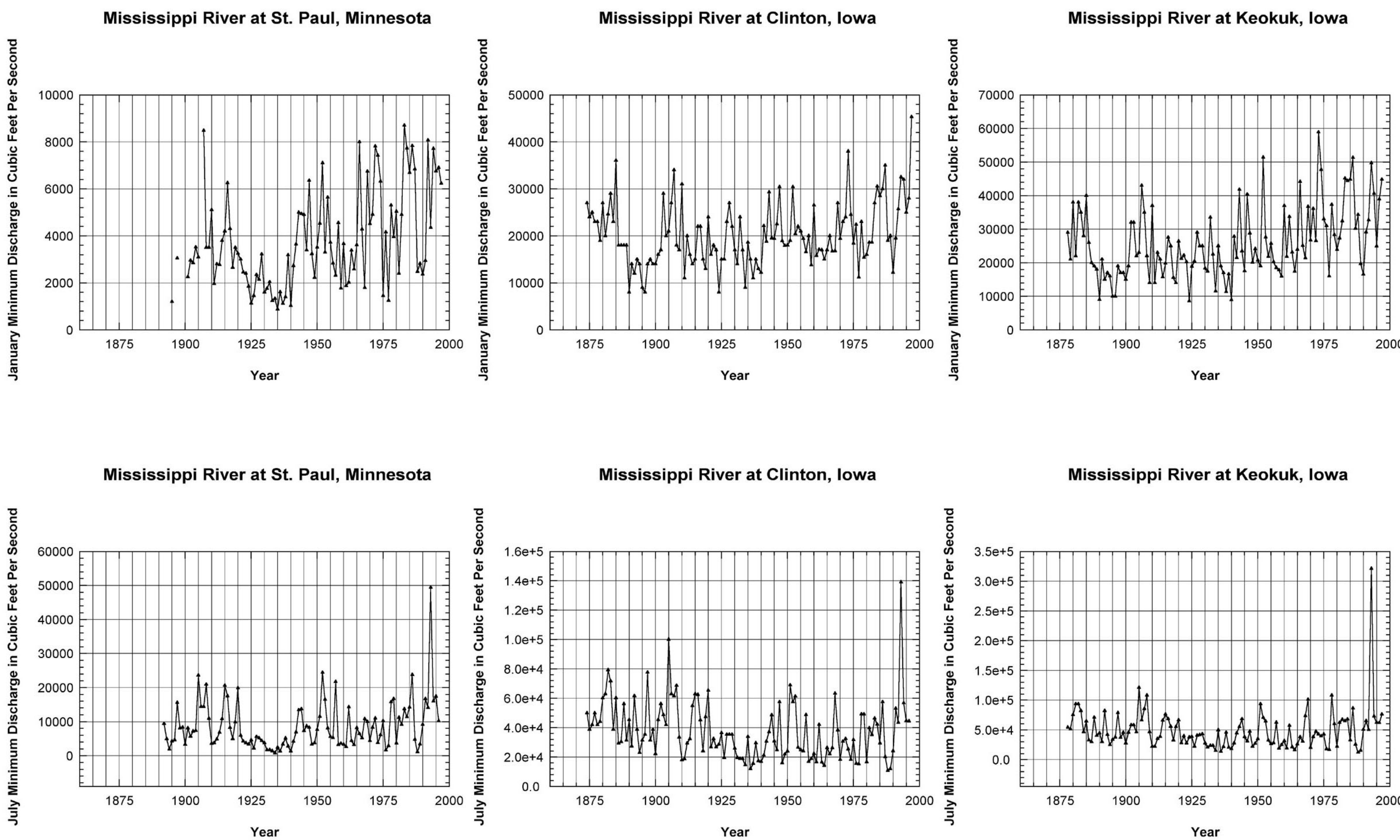


Figure 3-6: Minimum average daily discharge for January and July at three Upper Mississippi River U.S. Geological Survey gaging stations. (Note: ordinate scale changes between plots).

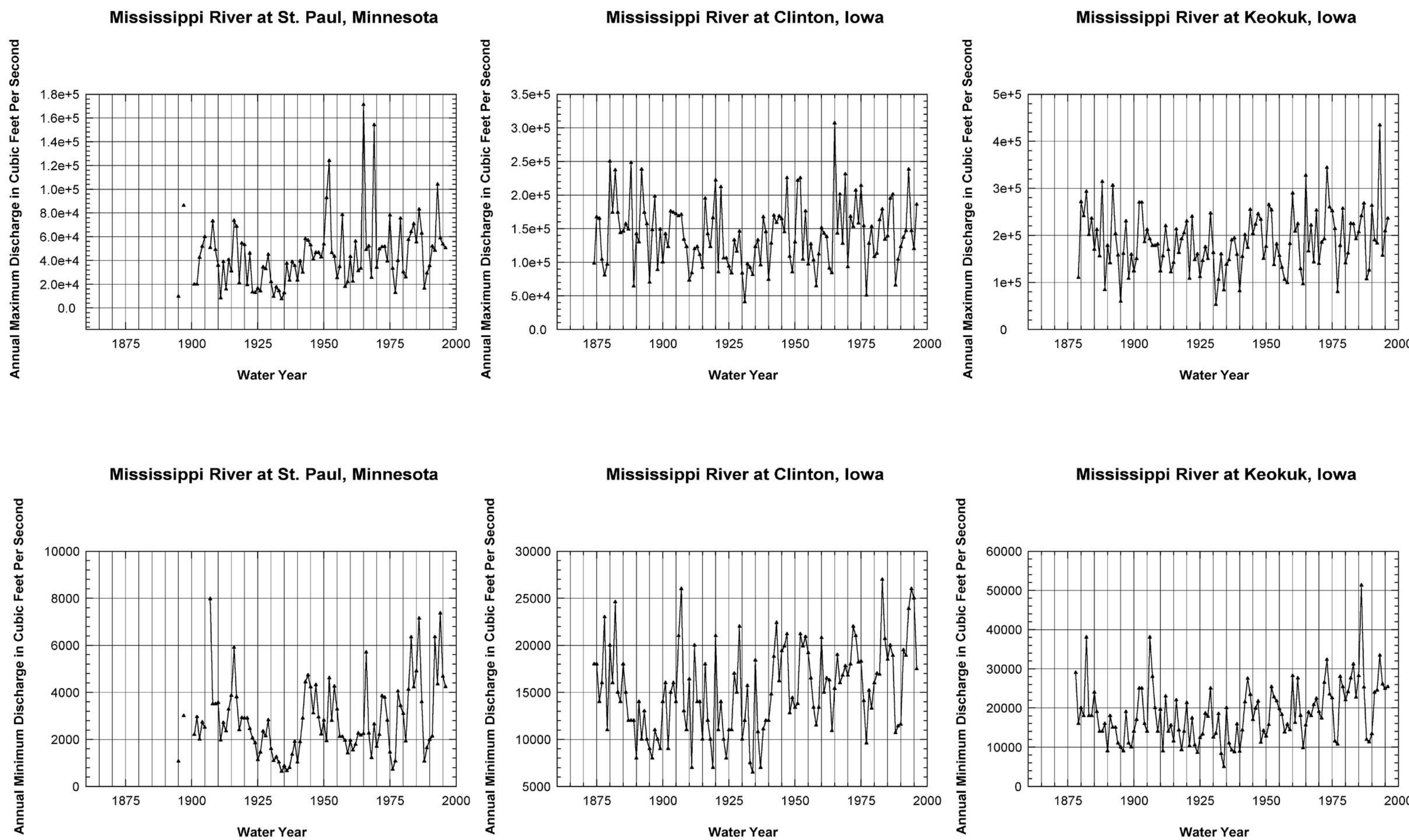


Figure 3-7: Annual maximum and annual minimum average daily discharge at three Upper Mississippi River U.S. Geological Survey gaging stations. (Note: ordinate scale changes between plots).

3.5.1.3 Annual Maximum Daily Average Discharges

Because of the large size of the associated watershed for the St. Paul, Clinton, and Keokuk gage sites, the annual maximum daily average discharge closely approximates the instantaneous annual maximum discharge. The data presented on Figure 3-7 show that the first half of the 20th century had relatively few extremely large floods on the upper Mississippi River compared to the period since about 1950. Figure 3-7 shows that St. Paul experienced six floods that exceeded 80,000 cfs since 1950, but none exceeded 80,000 cfs between 1900 and 1950. Since 1950, the Clinton gage recorded nine floods that have equaled or exceeded 200,000 cfs, but between 1900 and 1950 it recorded only three floods that exceeded 200,000 cfs. Farther downstream at Keokuk, there have been twelve floods that exceeded 250,000 cfs since 1950, but between 1900 and 1950 only three floods exceeded 250,000 cfs.

The uneven temporal distribution of large floods on the upper Mississippi River suggests that either a shift in climate or land use or both are influencing the occurrences of large floods. How much each is contributing to the uneven occurrence of large floods is unknown, but because the pattern of the very large floods closely matches the pattern of known changes in large-scale atmospheric circulation regimes, climate is indicated as an important contributor. A key assumption that underlies standard procedures such as the Log Pearson III method for calculating flood recurrence probabilities (U.S. Water Resources Council, 1981), is that floods occur randomly in time, and that environmental conditions that lead to their generation do not change over time. The data therefore suggest the assumption of relatively uniform environmental conditions may not be fully met.

3.5.1.4 Flow Records at St. Louis

According to Simons et al (1974), the net effect of all upstream human developments along the UMR, including locks and dams is reflected in the discharge records for the gage at St. Louis. The St. Louis gage is located downstream of all locks and dams and the Missouri River confluence with the UMR. Flow records for the St. Louis gage have been kept for over 133 years. Recently, the Corps of Engineers began a reevaluation of flood discharge and stage frequencies for the Lower Missouri and Upper Mississippi Rivers (Dieckmann and Dyhouse, 1998). That research indicates that flood peak discharges prior to 1931 were overestimated. Hence, comparison of flows measured prior to 1931 to those measured after 1931 is currently not possible. The Corps is currently working to revise the flow records (Personal communication with G. Dyhouse, 1998). Completion of the study is expected in the year 2000. Consequently, only the annual daily maximum, mean, and minimum flow at the St. Louis gage after 1931 were evaluated.

The annual daily maximum, mean, and minimum flow at the St. Louis gage since 1931 is shown in Figure 3-8. Changes in flow characteristics over the 1931 to 1994 period, include:

- Since 1931, only the Great Flood of 1993 has been in excess of 1,000,000 cfs.

- The mean annual discharge has trended upward over the time period. This indicates an apparent increase in the total volume of flow along the UMR and may be attributable to climate change (Knox et al., 1975). See Section 3.6 for a detailed discussion of the evidence for global warming and it implications for hydrologic and geomorphic change within the UMR basin.

- The annual minimum flow has been increasing steadily since 1931. The increase of minimum flow may be due to construction of a large number of water storage reservoirs on the tributaries to the UMR, release of stored water during low flow periods, and possibly, climate shifts.

In general, the conclusion can be drawn that man-made and natural influences have affected the maximum, average, and low flow conditions along the UMR at St. Louis. The specific influence of the reservoirs on discharge at St. Louis is currently being evaluated in an ongoing study as discussed previously.

3.5.2 Upper Mississippi River Stage

Theiling (no date) demonstrated that flow regulation caused by the locks and dams on the UMR reduces overall stage variation and seasonal cycles of stage within navigation pools. Low flow stages were shown to have increased from pre-lock and dam conditions, by between 1 to 4 meters, at the locations investigated. As an example, a five-year record of stage and discharge for pre-lock and dam (at River Mile 726) and post-lock and dam conditions at various locations in Pool 8 is shown in Figure 3-9. As seen from the figure, the flow regulation of the navigation dams affects high flow stages less. During high flows, most dams operate in an "open river" condition, where the gates of the dam are fully opened.

River stages have been measured intermittently at the St. Louis gage since 1843 and on a continuous daily basis since 1861. Simons et al. (1974) demonstrated that the annual maximum stage at the St. Louis gage has been increasing slightly throughout 130 years of records. The ten highest recorded stages and discharges for the UMR at St. Louis are summarized in Table 3-4. As seen from the table, the highest stages are not always associated with the highest historic flows. Increasing flood stages along the Open River segment of the UMR are attributed to man-induced narrowing of the UMR channel and confinement of the floodplain by levees. Simons et al. (1974) also found that annual minimum stages are trending lower throughout the period of record. Additional analysis of the effects of impoundment and river regulation related to ecological issues is presented in Volume 2.

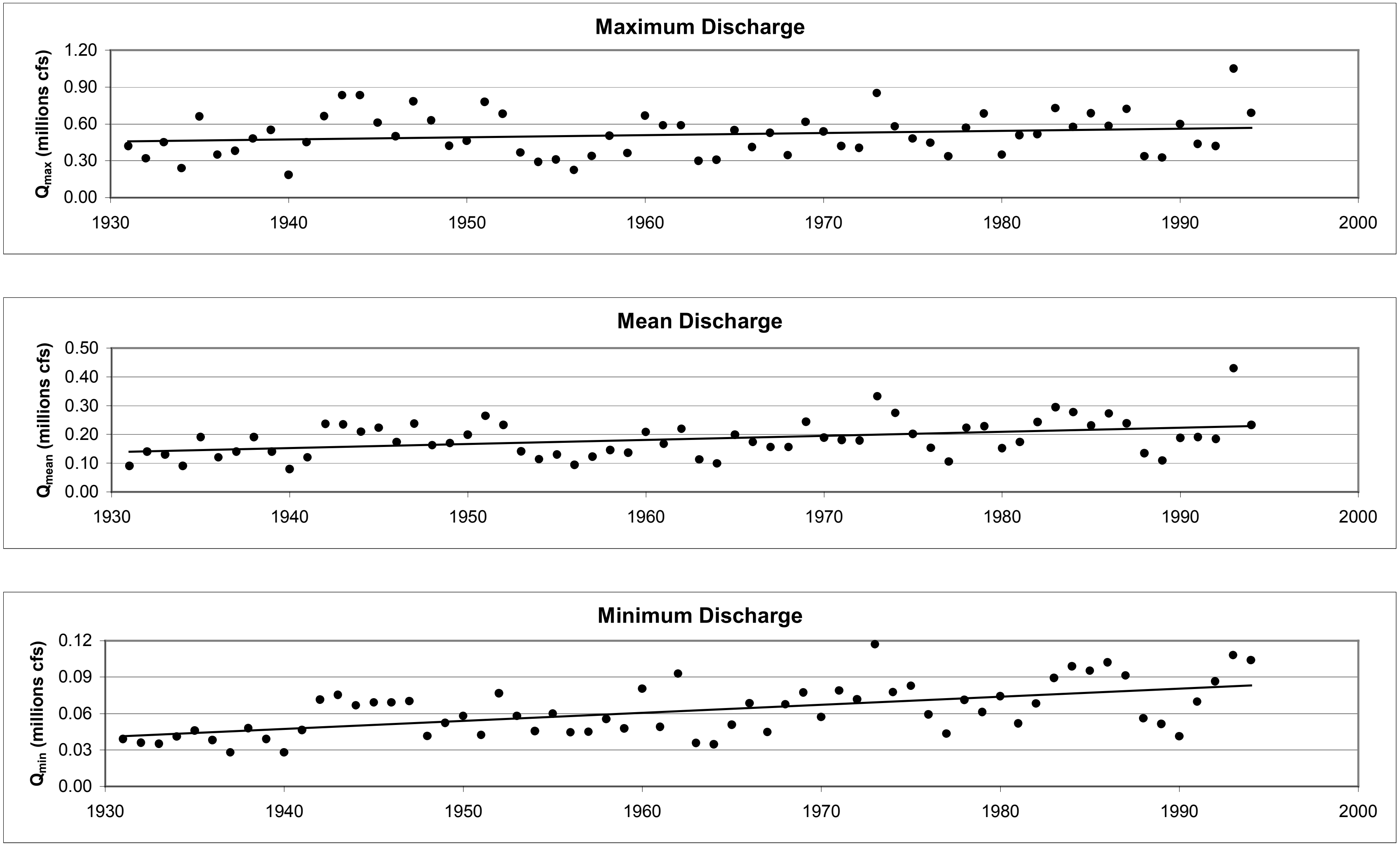


Figure 3-8: Maximum, mean and minimum discharge at St. Louis. (Source: EarthInfo CD database).

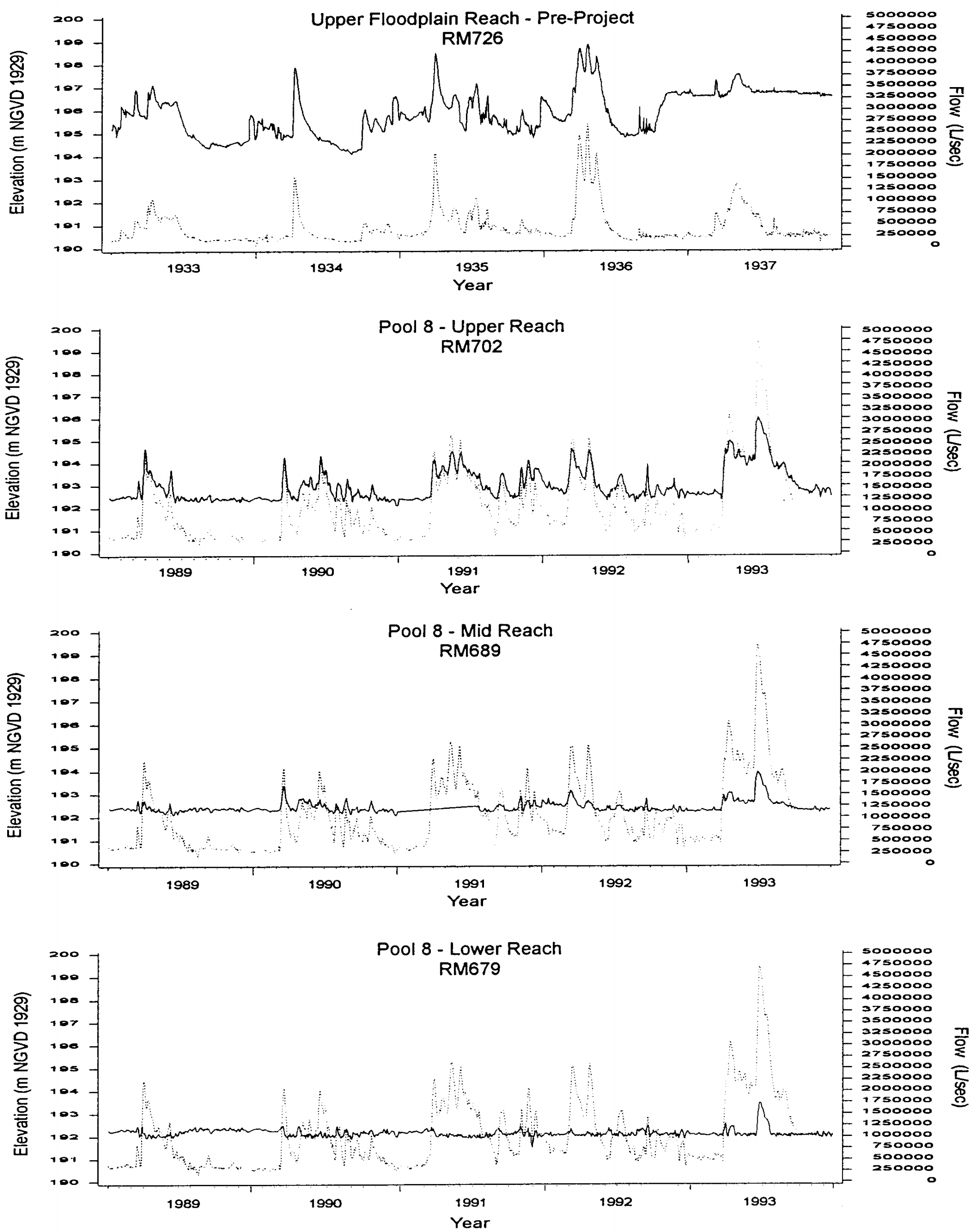


Figure 3-9: Five-year daily record of discharge and flow elevation at a location in Pool 6 and various locations in Pool 8. Dashed line represents discharge. Solid line represents river elevation (From Theiling, undated).

Table 3-4: The ten highest stages and flows at St. Louis, MO (Station 07010000).

Ten Highest Stages				Ten Highest Flows			
Rank	Date	Stage (feet)	Discharge (cfs)	Rank	Date	Discharge (cfs)	Stage (feet)
1	8/01/1993	49.58	1,070,000	1	8/01/1993	1,070,000	49.6
2	4/28/1973	43.31	852,000	2	6/27/1844	1,000,000*	41.3
3	6/27/1844	41.32	1,000,000*	3	6/10/1903	875,000*	38.0
4	7/21/1951	40.28	782,000	4	4/28/1973	852,000	43.31
5	7/01/1947	40.26	782,000	5	4/30/1944	844,000	39.14
6	5/04/1983	39.27	708,000	6	5/24/1943	840,000	38.94
7	4/30/1944	39.14	844,000	7	1892	834,000**	N/A
8	10/09/1986	39.13	728,000	8	4/29/1927	825,000**	36.1
9	5/24/1943	38.94	840,000	9	7/21/1951	782,000	40.28
10	6/10/1903	38.00	875,000*	10	7/01/1947	782,000	40.26

* These revised estimates were furnished to the USGS in 1998 to modify their records (Personal communication with G. Dyhouse, 1998).
** Preliminary estimates (Personal communication with G. Dyhouse, 1998).

3.6 GLOBAL WARMING

Since precipitation and temperature control the amount and type of runoff, climate is arguably the dominant factor controlling river hydrology. As the UMR basin is influenced by major seasonal air mass boundaries and storm tracks, and because it is crossed by two natural vegetation ecotones, it is an especially climatically sensitive region (Bryson, 1966). The trend and magnitude of climate change is therefore of great significance to the evolution of physical and ecological conditions along the UMR.

In the following sections, a discussion of global warming relevant to the UMR basin is presented. First, the results of several recent studies are reviewed describing the relative magnitude of global warming and impacts to rainfall and seasonal temperature. Second, the influence of historic climate shifts on the occurrence of large floods is described. Third, the geologic record is examined as evidence of how floods in the UMR responded to past climate changes for time intervals that are much longer than the available instrumented records. Fourth, the differences between floods associated with past periods of climate change and the current period of global warming are noted. Possible relations between global warming and the trend for various hydrologic data are described. Finally, the general conclusions that can be drawn from the current knowledge of global warming and the implications of global warming for the UMR system are reviewed.

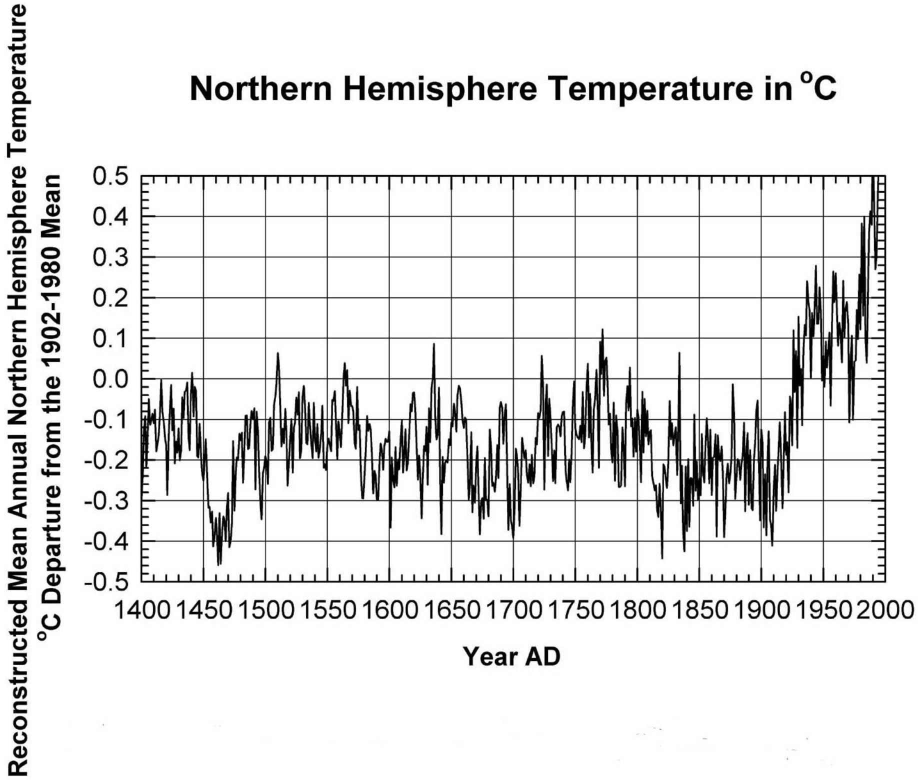


Figure 3-10: Mann et al. (1998) record of Northern Hemisphere mean temperature departures from the average for the period 1902-1980 shows that the 20th century warming is unprecedented in the previous five centuries.

3.6.1 Recent Studies

There has been an increasing awareness that human contributions to atmospheric greenhouse gases are resulting in global warming that in turn is contributing to changes in atmospheric and oceanic circulation regimes. A recent publication by Mann et al. (1998) places the instrumented record of global warming in a longer term context that illustrates the dramatic warming of the 20th century (Figure 3-10). Mann et al. (1998) used proxy climatic data, including tree rings, ice layers, corals, *etc*., to extend the record of Northern Hemisphere mean temperature back to AD 1400. This reconstruction shows that from AD 1400 until about AD 1920 the mean annual temperature of the Northern Hemisphere commonly was from 0.1 to 0.3 degrees Celsius below the mean annual Northern Hemisphere temperature for the 20th century. The data of Mann et al. (1998) show that after about 1920 mean annual temperature of the Northern Hemisphere rose rapidly until about 1950, then between about 1950 to about 1980 leveled off or slightly cooled, only to be followed by greatly accelerated warming since the early 1980s. Commenting on the extremely warm years of the 1990s, Mann et al. report that "Northern Hemisphere mean annual temperatures for three of the past eight years were warmer than for any other year since (at least) AD 1400." Karl et al. (1997) acknowledge that global average temperature has increased by about half a degree Celsius over the past century and they postulate that global average temperature could increase by an additional 1.0 to 3.5 degrees Celsius during the next century if current trends for increasing greenhouse gases continue.

Karl et al. (1997) suggest that changes in global average temperature are changing the patterns of atmospheric and oceanic circulation which, in turn, have influenced global patterns and occurrences of droughts and floods. Furthermore, Karl et al. (1995, p. 217) report that during the 20th century within the U.S. "...the proportion of total precipitation contributed by extreme, one-day events (greater than 50.8 mm/day) has increased significantly." This is not surprising because global warming is associated with a general poleward expansion of air masses characterized by high temperatures and high water vapor content.

Increasing the incidence of extreme rainfalls has the potential to degrade water quality and influence sedimentation conditions in the UMR basin. Intense rainfalls often result in accelerated soil erosion and sediment delivery from upland areas, particularly if the extreme rains occur over agricultural areas during the cultivation season. Karl et al. (1995, p. 219) found that while the increased delivery of precipitation in the extreme category occurred during all seasons in the U.S., it was especially characteristic of the summer (June-August) with spring (March-May) also contributing significantly.

Changes in mean seasonal temperatures can also influence whether precipitation is delivered as snow or rain and the melting rates for snow cover. Consequently, future global warming could significantly influence the magnitudes of seasonal maximum and minimum river discharges. Examination of maximum and minimum temperature trends by Easterling et al. (1997) has shown that the diurnal temperature range of the UMR watershed has been decreasing during the 20th century warming. The greatest changes in daily maximum and daily minimum temperatures have occurred in the northern part of the watershed where both have increased, whereas in the southern part of the watershed most of the change in daily temperature is due to increases in the minimum daily temperatures.

3.6.2 Historical Climate Shifts and Large Floods

The relative importance of changes in background climatic conditions to influence the probability distribution of floods can be tested against gage records. The long records of the three upper Mississippi River gage stations (St. Paul, Clinton, and Keokuk) include several climatic episodes involving changes in the types of large scale atmospheric circulation patterns known to either enhance or suppress occurrences of large floods. For example, the dates of about 1895, 1920, 1950, and 1980 are approximate times marking shifts in key patterns of large scale atmospheric circulation regimes and climate (Lamb, 1966; Kutzbach, 1970; Kalnicky, 1974; Knox et al., 1975; Knox, 1984; Mann et al., 1998). A detailed discussion of how particular synoptic patterns of large scale atmospheric circulation influence floods of the upper Mississippi River Valley has been presented elsewhere (Knox et al., 1975). For example, exceptionally large warm season floods in the upper Mississippi River Valley commonly are associated with enhanced development and persistence of an upper tropospheric trough of low pressure over the western to southwestern U.S. and with enhanced development and persistence of a warm-core high pressure system over the southeastern U.S. This situation results in the jet stream axis and main storm track being oriented from southwest to northeast over the central and upper Mississippi Valley where collision of polar and tropical air masses along the associated frontal zone commonly produce heavy, wide-spread, long-duration rains. The Great Flood of 1993 is an example of this process.

Figure 3-11 presents flood magnitude and frequency histograms of annual maximum floods for the Mississippi River gage at Keokuk. The independent record of climate episodes noted above was the basis for subdividing the Keokuk flood record into the five separate histograms. Between 1920 and 1949, when zonal westerly atmospheric circulation was of high frequency over the upper Mississippi Valley, large floods were infrequent. However, for the periods immediately before 1896 and after 1949, when the large scale tropospheric circulation involved a stronger meridional component that positioned storm tracks over the valley as noted above, large floods became more frequent. Qualitative examination of Figure 3-11 shows that while flood magnitudes for median to modal size vary rather conservatively between the climate episodes, floods representing the "tails" of the probability distributions are much more sensitive. Log Pearson III flood frequency probability analyses show that the estimated magnitudes for floods expected once per 50 years was 40-47% smaller during the period of prevalent zonal westerly flow (1920-1949) than during the preceding and following periods of weaker westerly circulation occurring before 1896 and after 1949 (Figure 3-11).

The differences in annual series flood magnitudes between climate episodes found for the Keokuk gage at Lock and Dam 19 are nearly identical to results found for differences in partial duration flood series for the St. Paul record far upstream in Pool 2 (Knox, 1984). The St. Paul results showed that the differences in magnitudes and frequencies of floods between climate episodes were associated with relatively small differences in mean annual temperature and mean annual precipitation. The difference between the mean temperatures of the warmest and coldest episodes was only 1.2 degrees Celsius (Knox, 1984, p. 323). As might be expected, the results also showed that mean annual precipitation does not correlate strongly with flood magnitudes because the majority of floods are snowmelt related. However, results confirm that the more extreme floods usually occurred during cooler years when above average precipitation in the preceding year is coupled with continued above average precipitation in the year of the large flood.

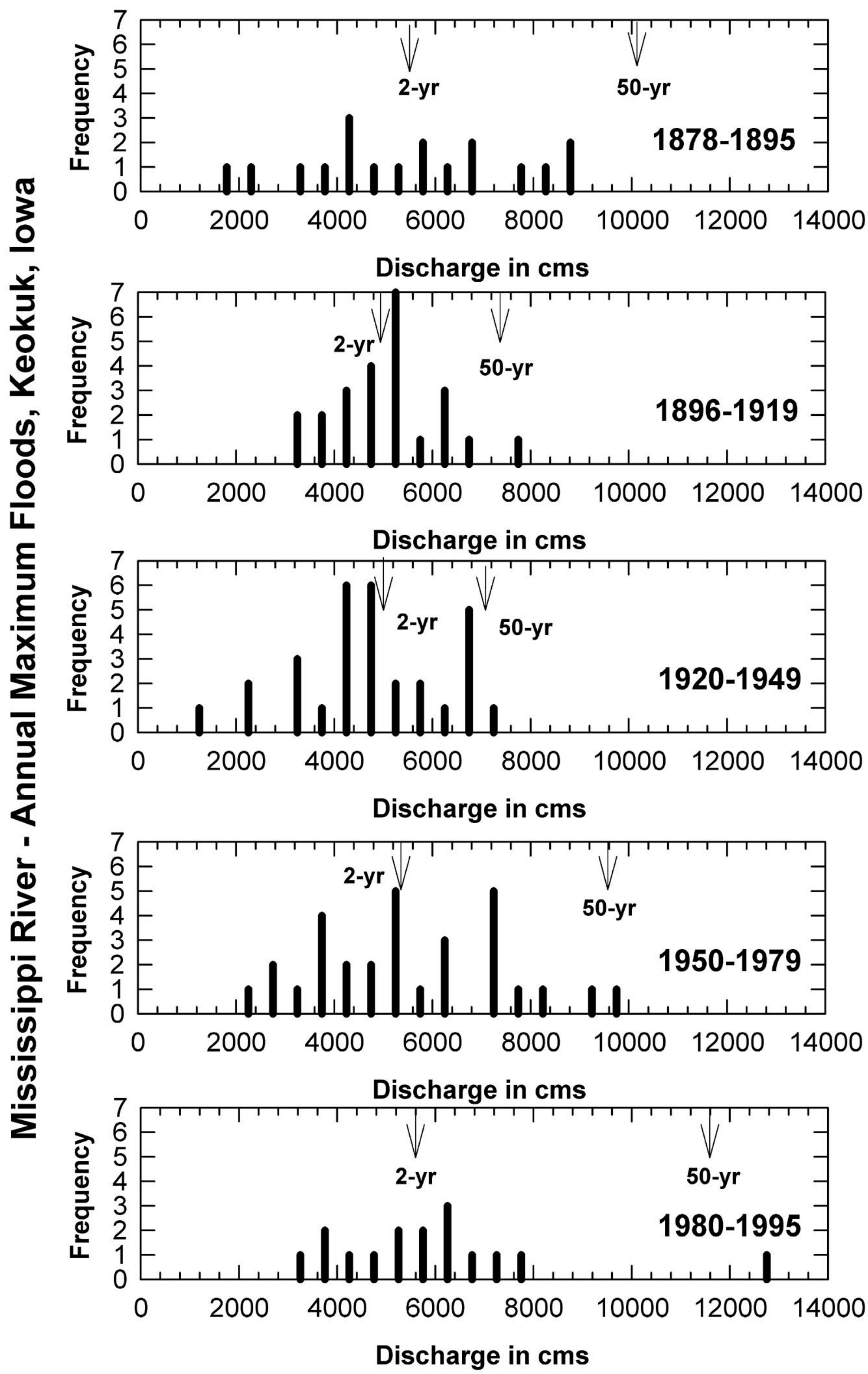


Figure 3-11: Distribution of annual maximum floods by climatic episodes (after Knox, 1996b; AMQUA presentation). Flood recurrence probabilities based on Log Pearson III method (U.S. Water Resources Council, 1981).

3.6.3 Response of Floods to Climate Change During Post-Glacial Time

The geologic record of floods from UMR tributaries along southwestern Wisconsin provides evidence of how floods responded to past climate changes for time intervals that are much longer than the available instrumented records. Fossil vegetation and fossil isotopes of carbon and oxygen are climate proxies. These proxies indicate that past climate changes of the same order of magnitude or smaller than climate changes expected from global warming over the next century have been associated with major shifts in magnitudes and recurrence frequencies of floods in the upper Mississippi River system. The details of these associations have been presented elsewhere (Knox, 1985a; 1993; 1996a).

The sensitivity of floods to changes of climate is illustrated by the following examples. First, it is noteworthy that during many past prolonged warm episodes flood magnitudes tended to decrease. This relationship is illustrated very well by the period between about 5500 and 3300 years ago (Figure 3-12 and Figure 3-13). Climate reconstruction from fossil vegetation (Winkler et al., 1986; Bartlein et al., 1984) and fossil isotopes of carbon and oxygen preserved in speleothem calcite (Dorale et al., 1992 Baker et al., 1996) indicate that during this period mean annual precipitation was about 15% less than modern, July temperature was about one-half a degree Celsius warmer than modern, and warming at the beginning of the period may have been as much as 1.5 degrees Celsius above the previous cooler period. The corresponding magnitudes of bank full stage floods on small tributaries averaged about 15 % smaller than their modern counterparts then (Figure 3-12). The smallness of overbank floods in the same region was even more dramatic. Nearly all identified paleoflood deposits indicated that floods during this approximately 2,000 year long interval had magnitudes that did not exceed the magnitude of a modern flood expected once in a 50-year period (Figure 3-13).

The period of small floods ended about 3,300 years ago when the climate shifted to cooler and moister conditions (Figure 3-12 and Figure 3-13). At the same time, very large overbank floods also began occurring, with many tributaries showing flood magnitudes equivalent to modern floods expected only once in 500 years (Figure 3-13). The fossil proxy climate indicators noted above suggest that about 3300 years ago precipitation increased to approximately its modern value and mean annual temperature may have decreased by about 0.7 degrees Celsius but later increased gradually by about 0.4 degrees Celsius (Winkler et al., 1986; Bartlein et al., 1984). The large post-glacial variations in flood magnitudes for these tributaries were therefore associated with relatively modest changes of climate involving changes of mean annual temperature not greater than 1-2 degrees Celsius and changes of mean annual precipitation of about 15-20 percent or less. Changes of this order of magnitude approximate magnitudes of climate change projected for the upper Mississippi River system by some global circulation model experiments if atmospheric greenhouse gases were to double. Karl et al., (1997, p 79), for example, stated "...because populations, national economies and the use of technology are all growing, the global average temperature is expected to continue increasing, by an additional 1.0 to 3.5 degrees C by the year 2100." The strong potential for continued global warming and demonstrated high hydrologic sensitivity suggests that additional study of hydrologic responses to climate changes could be very helpful for anticipating future management problems on the upper Mississippi River system.

3.6.4 The Anomaly of Large Floods and Global Warming

The geologic record of floods described in Figure 3-12 and Figure 3-13 demonstrates high sensitivity of hydrology to modest changes in climate. It is interesting, however, that the geologic record for the UMR basin indicates that past warm periods were generally characterized by fewer and smaller floods. The tendency for small floods for the relatively warm historical period 1920-1949 also represents a similar relationship. It is therefore intriguing that the accelerated global warming of the 20th century seems to be associated with a trend toward more frequent large floods (Figure 3-7 and Figure 3-11).

The discrepancy between small floods of past warm periods versus the large floods for recent accelerated warming of the late 20th century might be explained by the fact that recent warming has also been associated with increased precipitation for much of the upper Mississippi River system (Karl et al., 1997). It might also be due to strong forcing effects on atmospheric circulation patterns caused by the very rapid pace of warming. Model experiments often show that rapid forcing can result in unstable atmospheric circulation regimes with strong meridional components capable of generating large floods or extreme droughts in closely spaced time intervals. Perhaps the relatively short-term high variability evident in the annual maximum and annual minimum daily flows of the 1970s, 1980s, and 1990s for St. Paul, Clinton, and Keokuk flow gages is an example of climatic instability associated with the rapid pace of warming. The answer, of course, is unknown at this time.

Overpeck (1996) has suggested that "...the biggest potential warm-climate surprises in coming decades are likely to be linked with the continental hydrologic cycle." Overpeck cites evidence of others to show post-glacial droughts that were more severe and persistent than any represented in instrumented records have affected extensive areas of the Great Plains. A noteworthy example is Laird et al.' (1996) documentation of drought intensity and frequency over the past 2,300 years along the northeastern margin of the Great Plains near the North Dakota - Minnesota border on the western margin of the upper Mississippi River watershed. Using fossil diatoms as a sensitive index of changes in lake salinity, Laird et al.' (1996) found that extreme droughts of greater intensity than that of the 1930s were more frequent before AD 1200. Several of these extreme droughts persisted for longer than a century, as occurred between AD 200-370, AD 700-850, and AD 1000-1200. The latter episode is coincident with the well-known Medieval Warm Period, a time when many regions of the world show evidence of anomalously warm climatic conditions.

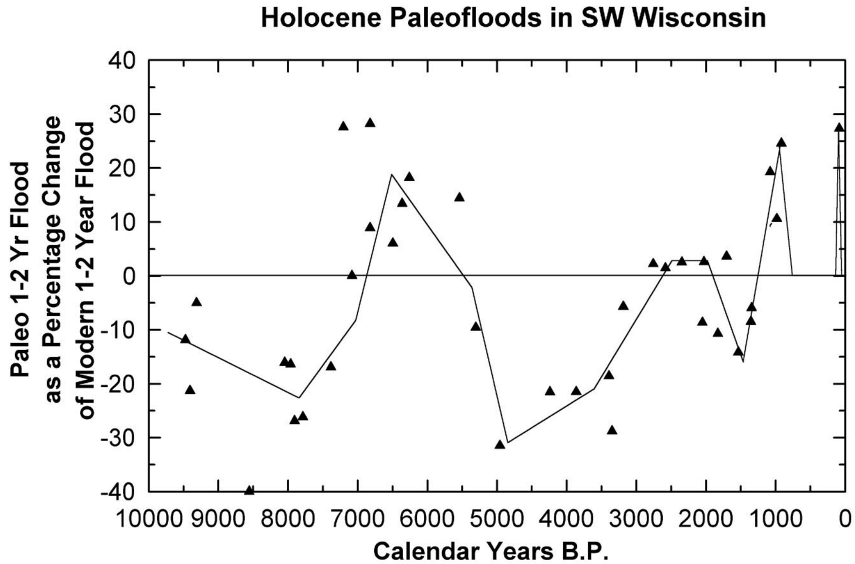


Figure 3-12: Relict floods with recurrence frequencies of approximately the bankfull stage were reconstructed from the dimensions of paleochannels. Ages were estimated by radiocarbon dating wood from bed deposits from related alluvial deposits (after Knox, 1985a; 1996a).

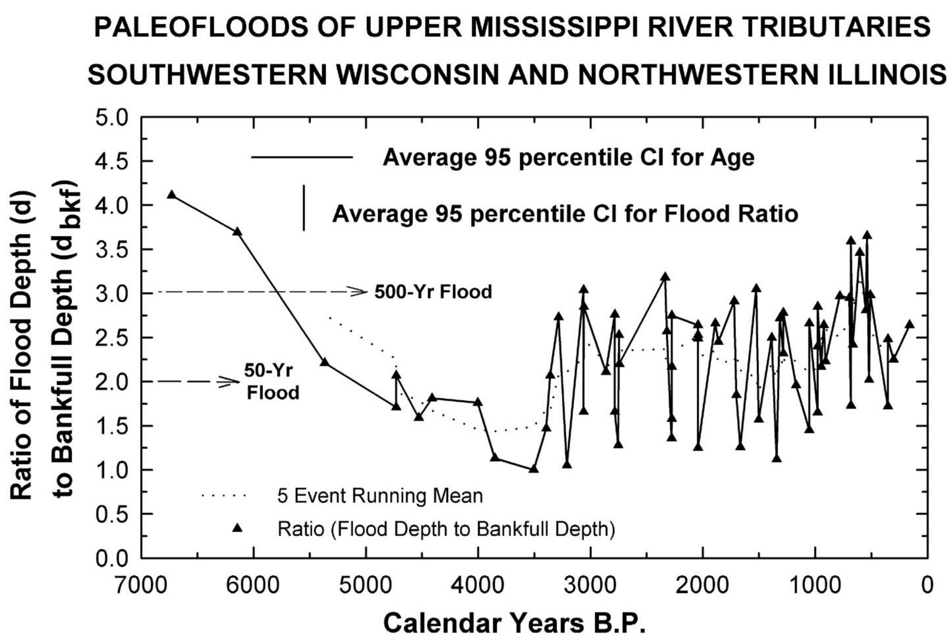


Figure 3-13: A long-term record of overbank floods on small tributaries of the Upper Mississippi River was determined from minimum water depths competent to transport flood deposited cobbles and boulders found deposited on floodplains. The 95th percentile confidence intervals are 870 years for age and 0.6 for the flood ratio (Figure modified from Knox, 1993; 1996a; see these references for methodology details).

3.6.5 Summary

Instrumented and proxy climate indicators (*e.g.,* tree rings) indicate that the 20th century is experiencing anomalous warming that is strongly influenced by globally increased concentrations of greenhouse gases in the atmosphere. There is a very high probability that the rapid warming trend will continue at least over the next 50 years as global population, economies, and technologies continue to advance (Karl et al., 1997). Modest contributions to warming from high solar forcing may also contribute to the warming trend (Mann et al., 1998). Research studies have shown that the 20th century global warming over the upper Mississippi River system has been associated with warmer winter and warmer night-time temperatures (Easterling et al., 1997). The warmer temperatures reduce snow cover and contribute to more of the cool season precipitation being delivered as rain than as snow. Increased magnitudes for the average daily low stage flows during the cool season may indicate that the warming is influencing the hydrology of the upper Mississippi River system.

Although the evidence presented in this report focuses mainly on river flows and floods, warmer winters and absence of snow cover would increase land surface exposed to erosion by surface runoff during winter and spring. Consequently, increased delivery of sediment to the Mississippi River could occur in spite of changes in land use that have favored reduced runoff and soil erosion over the past several decades (Argabright et al., 1996). Also of concern is the recent discovery that global warming has been associated with a greater portion of annual precipitation being delivered by extreme rainfalls (Karl et al., 1995). Continuation of this trend also implies a greater potential for surface runoff and soil erosion from the agricultural uplands of the UMR basin.

Studies of the relations between floods and climate changes show that even very modest climate shifts at both historical and geological time scales have typically resulted in important adjustments in the recurrence intervals of floods, especially for large floods (Knox, 1984, 1985a; 1993; 1996a). These variations in floods were associated with mean annual temperature shifts that are of the same order of magnitude or smaller than mean annual temperature shifts postulated to occur over the next 5-10 decades if current trends continue. Historical records of river discharges extending into the late 19th century show that the late 20th century river discharges along the UMR have been characterized by anomalously high frequencies of large floods. Their association with changes in recurrence frequencies for patterns of large scale atmospheric circulation regimes known to cause extreme floods in the upper Mississippi Valley suggests that climate change is a likely cause rather than land use change. Changes in flood magnitudes and recurrence frequencies have important consequences for the erosion, delivery, and deposition of sediment and contaminants in the upper Mississippi River.

Although specific physical and ecological impacts of altered hydrological conditions related to global warming are unknown at this time, the available data and information demonstrate a high level of sensitivity between the hydrologic conditions in the UMR basin and relatively modest changes in climate. There is a reasonably high probability that the climate of the next 50 years is not well represented in the existing instrumented records of climate and hydrology for the UMR basin. Thorough consideration of possible scenarios of climatic and hydrologic conditions that may be associated with continued global warming is likely to be useful for successfully addressing future river management issues.

4 HYDRAULIC ANALYSIS

An evaluation of hydraulic conditions within five navigation pools located along the UMR (Pools 5, 8, 13, 21, and 26) and one navigation pool along the IWW (LaGrange Pool) was conducted. Evaluations were only made for navigation pools having existing two-dimensional hydraulic models. The objective of the study was to define typical hydraulic characteristics associated with each aquatic class defined in Section 5.5. Specifically, the extent of three velocity classifications was determined for each pool evaluated. As explained in Volume 2, the results of the hydraulic evaluation are used to identify habitat areas associated with defined ecological guilds.

4.1 METHOD

The hydraulic analysis was accomplished by the application of the RMA2 two-dimensional hydrodynamic model (Thomas and McAnally, 1985). The model input data for each pool was obtained from two USACE Districts (St. Paul and Rock Island) and the USACE Waterways Experiment Station (WES). A RMA2 model for Pool 5 was obtained from the St. Paul District (Personal communication with Goodfellow, 1998). The RMA2 Models for Pools 13 and 21 were obtained from the Rock Island District (Personal communications with S. Johnson, 1998; Personal communication with T. Kirkeng, 1998; Personal communications with K. Landwehr, 1998; Personal communication with J. Burant, 1998). RMA2 Models for Pools 8 and 26 on the UMR and the LaGrange Pool on the IWW were obtained from WES (Personal communications with D. Abraham, 1998; Personal communication with G. Nail, 1998). The models were calibrated and verified by their original developers. No changes were made to the finite element geometry of the models. Each of the pools was modeled for a discharge equal to the 50 percent annual duration flow as determined from USGS daily flow data. The hydrologic estimates modeled for each pool were provided by the St. Paul District (Personal communications with S. Goodfellow, 1998) and Rock Island District (Personal communications with Johnson, 1998).

4.1.1 Model Coverage

For Pools 5, 13 and 21 the RMA2 model coverage extends between the associated locks and dams bounding each pool. For Pool 8, only the lower portion of the navigation pool is modeled. For Pool 26 and LaGrange Pool, an upstream portion of each pool is modeled. Graphical plots of the model coverage within each pool are shown in Appendix B. As seen in the figures presented in Appendix B, the models for Pools 8 and 13 were divided into two parts to facilitate hydraulic computations.

4.1.2 Boundary Conditions

The discharge modeled in each pool (50% annual duration flow) was prescribed as an inflow boundary condition at the upstream limit of the RMA2 computational mesh. Water surface elevations were prescribed at the downstream limit of each mesh as a tailwater boundary condition. The tailwater elevations were obtained from the St. Paul District (Goodfellow, 1998) and Rock Island District (Johnson, 1998). The eddy viscosity value was set constant throughout the flow domain for all pools. A Manning's *n* was prescribed as a function of depth in each pool modeled. The developer of the RMA2 model for each pool determined the values of eddy viscosity and Manning's *n* through calibration and verification. The boundary conditions used in each RMA2 model are summarized in Table 4-1.

Table 4-1: Boundary conditions for RMA2 models.

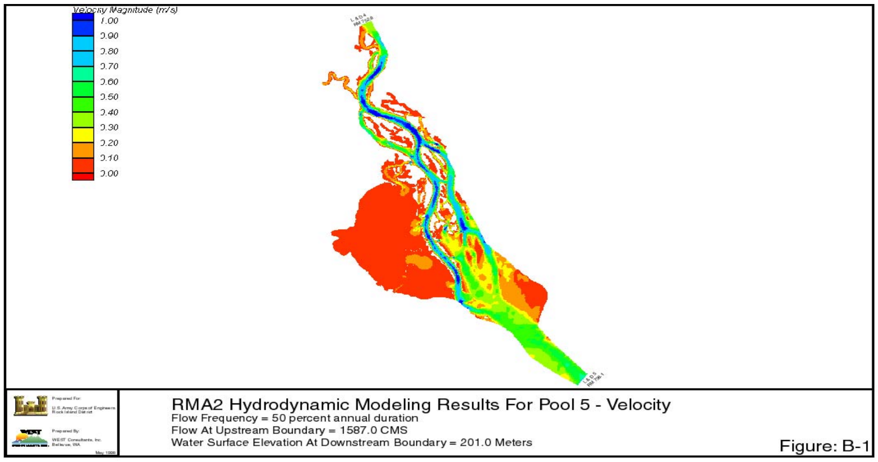
POOL	50% Duration Flow Conditions			
	Upstream		Downstream	
	River Mile	Flow (m^3/sec)	River Mile	Elevation (m)
5	752.8	879	738.1	201
8 (Upper)	697.5	889	688.6	192
8 (Lower)	688.6	889	679.1	192
13 (Upper)	556.7	1,048	531.0	100*
13 (Lower)	531.0	1,048	522.5	100*
21	343.2	1,416	324.9	143
26	232.3	2,322	221.7	130
LaGrange	99.4	340	92.9	131

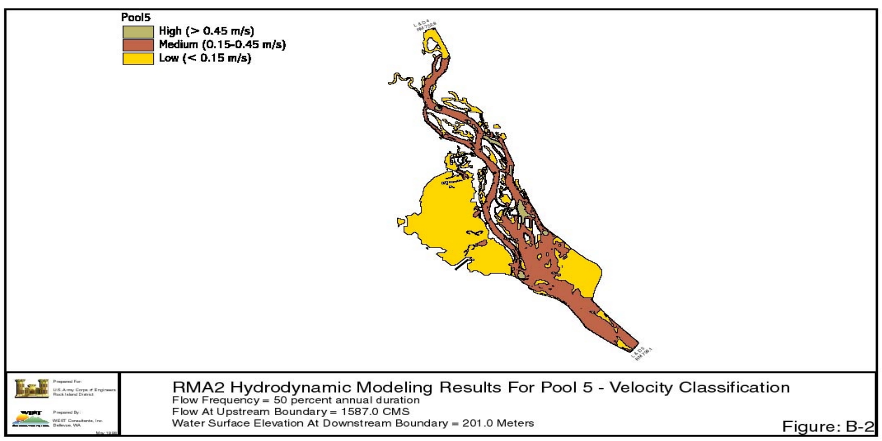
*Arbitrary datum elevation of 100 ft is used for Pool 13 (Landwehr, Rock Island District)

4.2 RESULTS

For each pool, a series of three plots describing the velocity magnitude, velocity classification and depth profile within the modeled reach were developed. Example plots for Pool 5 are shown in Figure 4-1. The plots for all pools are presented in Appendix B.

For use in the ecological analysis presented in Volume 2, the modeling results for the 50 percent annual duration flow were used to determine the flow velocity 10 cm above the channel bottom (Personal communications with S. Jutila, 1998). The calculated flow velocities were then classified into three categories defined as (Personal communication with D. Wilcox, 1998; see also Volume 2 of the report): Low Velocity (0.15 m/s and less); Medium Velocity (0.15 m/s to 0.45 m/s) and, High Velocity (0.45 m/s and higher). The velocity classifications determine habitat conditions for several fish species, based on U.S. Fish and Wildlife Service (USFWS) Habitat Suitability Index (HIS) models (see detailed discussion in the ecological assessment section). The area associated with each velocity category was then delineated using a geographical information system. The distribution between velocity categories defined within the portion of each pool modeled and among the three aquatic classes considered [Main Channel (MC), Secondary Channel (SC) and Contiguous Backwater (CB)] is summarized in Table 4-2 (aquatic classes are defined in Section 5.5). It is observed from the table that larger areas of high velocity are generally found in the upper portion of each pool. The contiguous backwater aquatic class has the largest area of low velocity. Overall, areas of medium velocity are the largest within most of the pools. The average values for the velocity delineation for the pools were used in the ecological assessment analysis. Improvement of these estimates would require modeling of more pools.





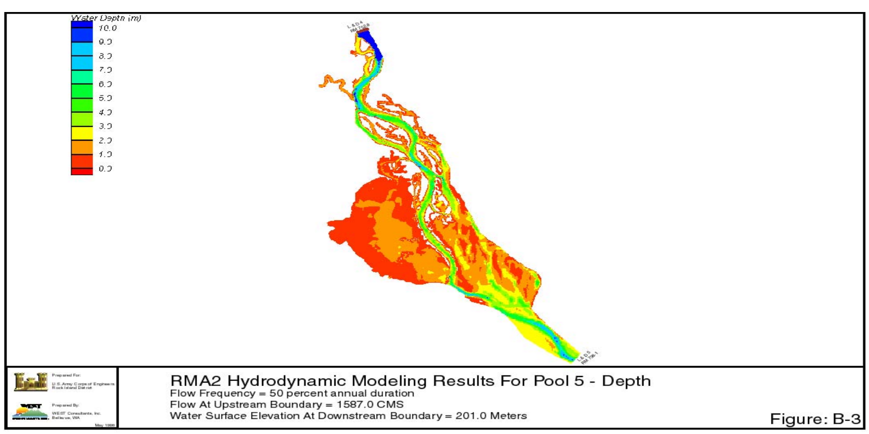


Figure 4-1: Plots of velocity magnitude, velocity classification and depth profile for Pool 5. Complete set of plots for all pools modeled are presented in Appendix B.

Table 4-2: Distribution of velocity categories in modeled pools 10 cm above the bottom.

Pool	Aquatic Class*	Upper Pool**				Lower Pool**			
		Area (m^2)	Percent of area within each velocity category			Area (m^2)	Percent of area within each velocity category		
			High	Medium	Low		High	Medium	Low
			> 0.45 m/s	0.45 - 0.15 m/s	< 0.15 m/s		> 0.45 m/s	0.45 - 0.15 m/s	< 0.15 m/s
5	MC	5,047,705	4%	78%	17%	9,113,166	2%	92%	7%
	SC	4,691,809	15%	61%	24%	0			
	CB	18,368,869	0%	9%	91%	2,682,568	0%	0%	100%
8	MC	6,231,267	10%	84%	5%	45,122,539	12%	78%	11%
	SC	1,039,138	26%	42%	33%	284,523	20%	80%	0%
	CB	20,835,852	0%	29%	71%	4,447,120	28%	50%	23%
13	MC	8,658,998	2%	94%	5%	56,026,572	0%	41%	59%
	SC	788,304	6%	83%	11%	2,357,428	2%	57%	42%
	CB	1,445,805	0%	2%	98%	21,467,739	0%	18%	82%
21	MC	11,050,729	6%	71%	23%	7,907,745	13%	73%	14%
	SC	6,683,659	6%	73%	21%	0			
	CB	0				0			
26	MC	9,647,386	35%	65%	0%	N/A			
	SC	6,850,459	26%	71%	3%	N/A			
	CB	0				N/A			
LaGrange	MC	305,835	0%	58%	42%	N/A			
	SC	60,131	0%	53%	47%	N/A			
	CB	2,388,800	0%	1%	99%	N/A			
Totals	**MC**	40,941,920	12%	77%	10%	118,170,022	6%	61%	33%
	SC	20,113,500	16%	68%	16%	2,641,951	4%	59%	37%
	CB	43,039,326	0%	18%	82%	28,597,427	4%	21%	74%

* MC = Main Channel; SC = Secondary Channel; CB = Contiguous Backwater.
** Definition of Upper and Lower Pool is given in Section 5.5.1.

5 GEOMORPHIC ANALYSIS

In this chapter, the geomorphology of the UMR basin is discussed. First, the geology and soils within the basin are described. Second, the human influences on the UMR system are characterized. Third, the sediment transport characteristics of the system are defined. Fourth, an analysis of historical plan form change is presented. Finally, an analysis of channel cross section data is made.

5.1 GEOLOGY

The upper Mississippi River basin has been repeatedly impacted by glacial ice during the last 2.5 to 3.0 million years (Figure 5-1). The continental glaciers eroded and deposited great masses of sediment and in many instances, they were responsible for major adjustments in the direction and patterns of river drainage. In pre-glacial time, the southward course of the Mississippi River along extreme southwestern Wisconsin and extreme northwestern Illinois appears to have not existed. However, a major displacement of the Mississippi River from its southeastward course to join the present-day Illinois River at the big bend in north-central Illinois only occurred about 20,000 years B.P. (before present). Although it has been about 10,000 years since glacial ice last left the northern extremities of the Mississippi basin, the legacy of past glaciations continues to dominate the physical behavior of the Mississippi River. These effects are particularly noteworthy in the longitudinal profile of the river between St. Paul, Minnesota and Cairo, Illinois (Figure 5-2).

The southward course of the Mississippi River from Minnesota to southern Illinois is superimposed on geologic structures and rock strata of variable erosional resistance. This variability, in association with river diversions caused by glacial ice, accounts for the large reach to reach variability in valley morphology and river characteristics. A regionally dominant bedrock structure is the broad-scale gentle upwarping of rocks centered on a north-south trending axis through central Wisconsin. The regional dip of the bedrock in southwestern Wisconsin is about 18 feet per mile to the SSW (Heyl et al., 1959). In northern Illinois, the rocks have a more southerly dip as they reflect regional downwarping into the broad structural basin that underlies the state of Illinois. Long-term geologic erosion of the gently dipping bedrock strata has resulted in somewhat circular patterns of ridge lines (cuestas) representing the more resistant dolomite rock formations (Figure 5-3).

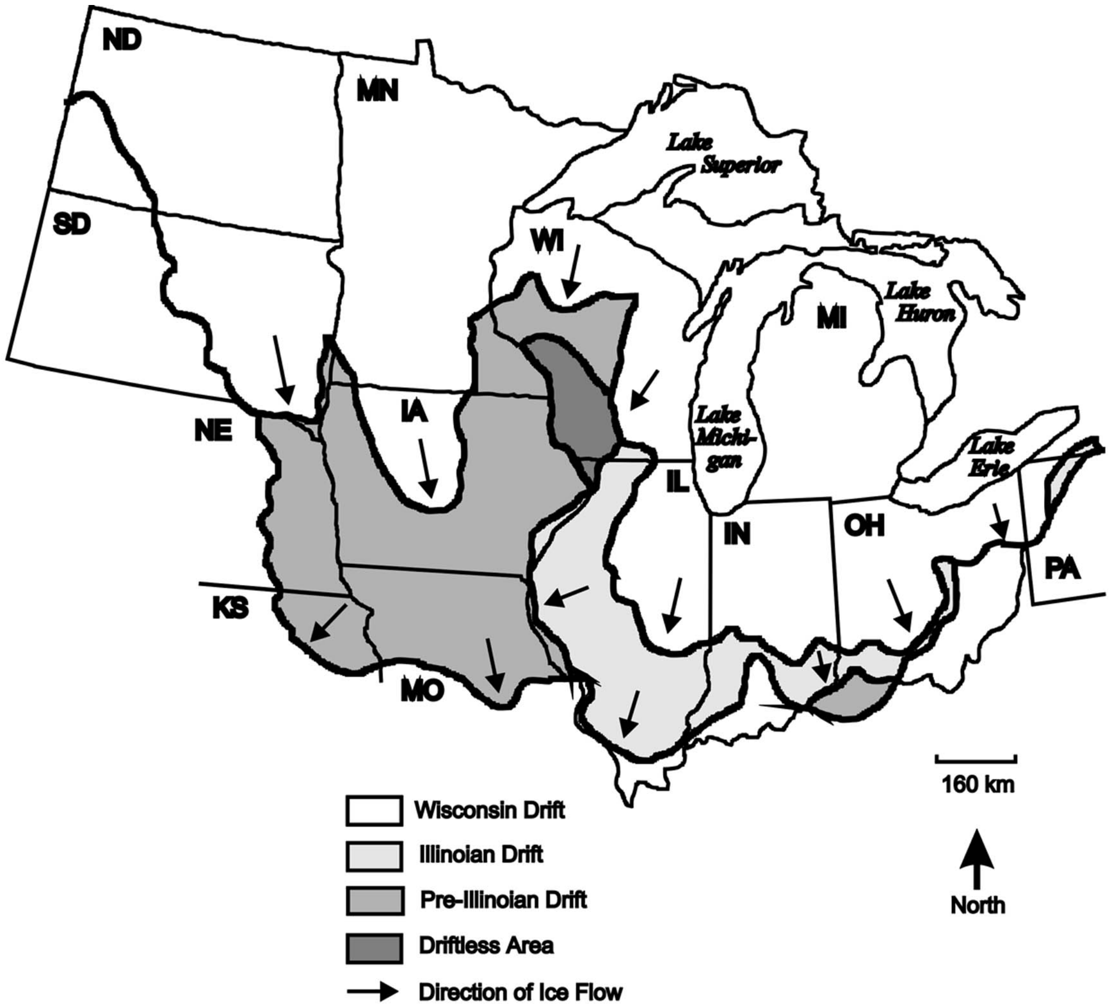


Figure 5-1: Pleistocene glacial deposits in the Midwest United States. Data Sources: Dyke and Prest, 1987; Fullerton, 1986; Gray et al., 1991; Hallberg, 1986; Johnson, 1986; Knox and Attig, 1988; Mickelson, 1987; Mickelson et al., 1983; Ruhe, 1969; Thornbury, 1965; and Whitfield et al., 1993.

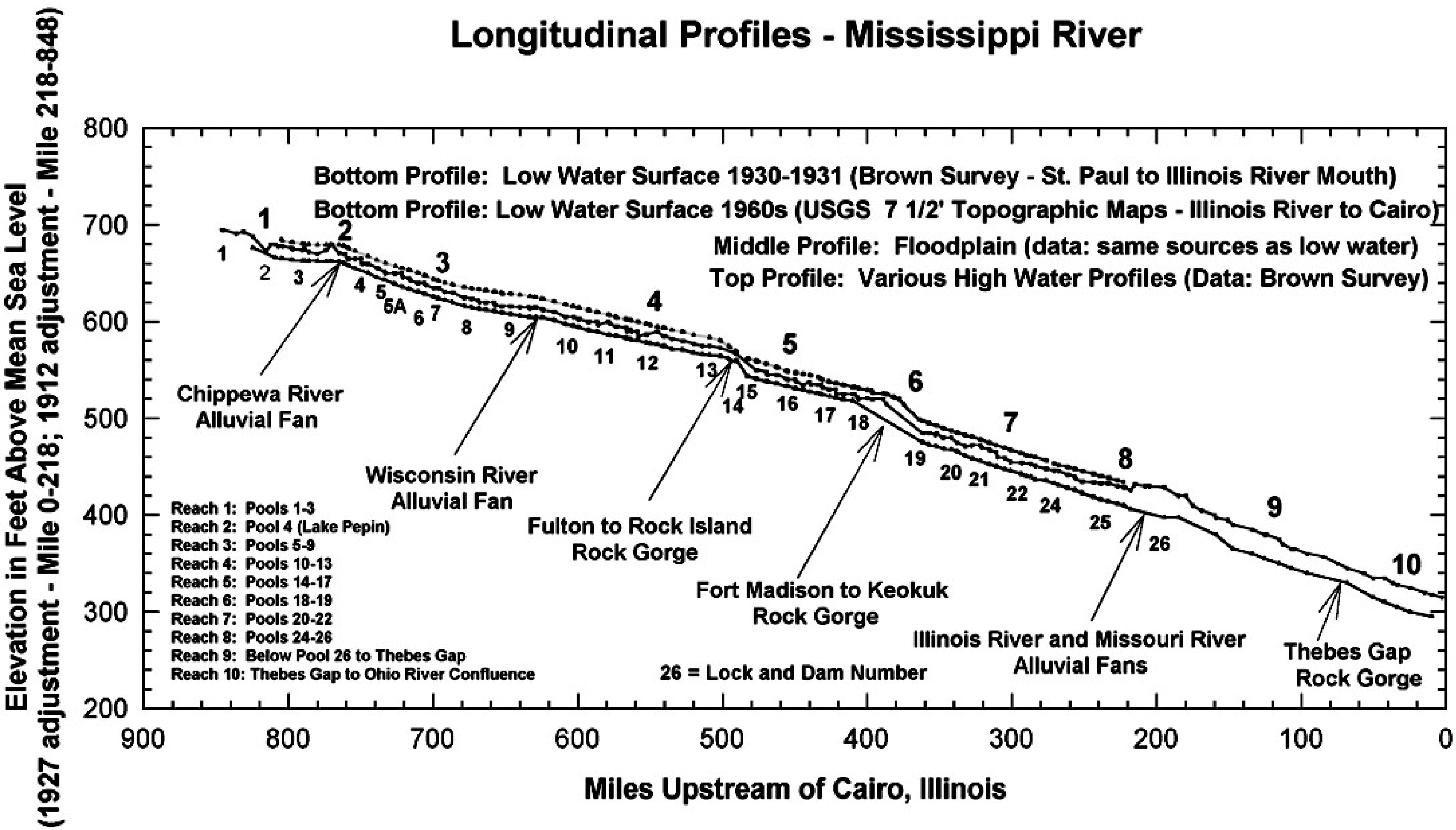


Figure 5-2: The upper Mississippi River is divided into 10 geomorphically based reaches that reflect the river's adjustment to glacial events and other geological controls in the region.

The cuesta that is capped by the dolomite rocks of the Galena and Platteville formations is intersected by the Mississippi River near the mouth of the Wisconsin River. The strong erosional resistance of the dolomite rocks causes the Mississippi River to flow in a very narrow rock gorge at this point. Similarly, the cuesta on the resistant dolomite of the Niagara formation trends southeastward in northeast Iowa and then eastward across northern Illinois (Figure 5-3). Because the Mississippi River is incised across these cuestas, rather than being deflected by them, it is said to be "out of accordance with structure" (Anderson, 1985, 1988). Consequently, Mississippi River valley side bluffs along Pools 10, 11, and 12 are quite resistant to erosion and the river flows in a narrow gorge for most of this section. Further north, less erosionally resistant sandstones crop out on the valley sides. Here the valley tends to be much wider and more open in character.

The lower middle reaches of the upper Mississippi River valley anomalously widen occasionally even where strong, erosionally resistant rock formations crop out in the valley walls. These anomalously wide valley reaches are associated with the coincidence of the modern valley with geologically old pre-glacial valley segments. The long expanse of a narrow, steep-walled valley reach along southwestern Wisconsin and northwestern Illinois is geologically young and appears to have formed since the first glaciers invaded the region between 2.5-3.0 million years ago. Glacial outwash gravel from a WNW source direction occurs on bluff tops along the eastern side of the Mississippi River in southwestern Wisconsin and northwestern Illinois and probably was deposited prior to incision of the river gorge at these locations (Willman and Frye, 1969; 1989; Knox, 1985b). Although the glacial gravels suggest a young age for the valley here, glacial sediment in buried incised valleys of northeastern Iowa is thought to be about 500,000 years old (Hallberg et al., 1985) and some glacial related sediment in the gorge of the lower Wisconsin River is at least about 790,000 years old (Knox and Attig, 1988). Since the sediment in the lower Wisconsin River occurs near the level of the modern floodplain, the valley must have been incised at least to that level by about 790,000 years ago.

It is apparent the pre-glacial course of the Mississippi River was the middle and lower Illinois River downstream of its big bend in north-central Illinois (Thornbury, 1965, p. 214-215). Deeply buried ancient valleys trend southeastward across central Iowa. The ancient Wapsipinicon River extended eastward across the present course of the Mississippi River into western Illinois to join the ancient Mississippi-Illinois system (Figure 5-4). Prior to glaciation, the northern bedrock divide of the Mississippi watershed may have been the Niagaran cuesta that crosses the present Mississippi River near Savanna (Figure 5-3). Ponding in front of one or more of the early glaciations (Willman and Frye, 1969; 1989; Knox, 1985), possibly coupled with isostatic forebulge caused by ice loading (Anderson, 1988), caused meltwater to flow over and downcut through the bedrock cuestas. Prior to this time the headwaters of the modern Mississippi River in Minnesota and western Wisconsin may have drained northward to Hudson Bay or possibly eastward to the Atlantic.

It was once believed there were four major stages of glaciation during the glacial period, but now it is recognized that at least six pre-Illinoian glaciations have occurred in Iowa and Nebraska. Because age control is problematic for these older glaciations they are lumped together in the category "pre-Illinoian" (Richmond and Fullerton, 1986). Pre-Illinoian glaciation extended as far south as the Missouri River. The Illinoian glaciation which occurred between about 300,000 and 130,000 years ago (Johnson, 1986), temporarily diverted the Mississippi River out of its existing course. Until the beginning of Illinoian glaciation the Mississippi River flowed southeastward across northwestern Illinois to the present Illinois River and then southward along the present Illinois River to the present Mississippi River. The Illinoian glacier expanded southwestward across Illinois into eastern and southeastern Iowa (Figure 5-1). Meltwater drainage was then routed across the uplands of southeastern Iowa along the Illinoian ice front (Hallberg, 1980). Willman and Frye (1970, p. 28) note that Illinoian glaciation caused diversions of the Mississippi River at Rock Island, Warsaw, St. Louis, and Fountain Bluff. Following Illinoian deglaciation, the Mississippi River returned to its original course through central Illinois along the course of the present Illinois River. Glaciers of Wisconsin age began to influence the Mississippi River by about 55,000 years ago (Leigh and Knox, 1993).

Westward expansion of glacial ice, in northeastern Illinois about 20,000 years B.P., blocked the Mississippi River near the big bend in north-central Illinois (See Figure 5-4). A lake that formed in front of the glacier subsequently drained southeastward into the ancient Iowa River, then southward to rejoin the Mississippi Valley at the mouth of the present-day Illinois River. The steep, rocky-bed reach of the Mississippi River in Pools 14 and 15 is associated with this flow diversion. The narrow gorge and pre-dam, steep, longitudinal gradient on rocky rapids that existed in Pool 19 also resulted from diversion of the Mississippi River by glacial ice. However, the diversion at Pool 19 is older and is associated with the Illinoian Stage of glaciation (Willman and Frye, 1970). The diversion through Thebes Gap into Reach 10 (Figure 5-2) resulted from a large flood associated with rapid drainage of an ice-marginal lake, probably between about 12,000 to 11,000 radiocarbon years B.P (Porter and Guccione, 1994; Royall et al., 1991).

By about 25,000 years B.P. glacial ice advanced again into the basin of the Mississippi River and remained until about 14,000 years B.P. (Johnson, 1986; Hallberg and Kemmis, 1986; Leigh and Knox, 1994; Teller, 1987, Wright, 1987, Knox, 1996a). This late Wisconsin glaciation produced massive aggradation of the upper Mississippi River. The landform representing the maximum elevation of this aggradational sequence is known as the Savanna Terrace in the upper Mississippi Valley (Flock, 1983). The Savanna Terrace is mainly found in the mouths of tributaries where it was protected from erosion by extreme floods caused by outlet failures of proglacial lakes during the late glacial to Holocene (post-glacial) transition (Knox, 1996a). From about Dubuque, Iowa (Pool 11) northward a series of terraces that were cut into deposits underlying the Savanna Terrace are identified as the Bagley Terrace sequence (Knox, 1996a). The Bagley terraces were cut by extreme floods and runoff resulting from rapid drainage of pro-glacial lakes between about 14,000 and 12,000 years B.P. Although erosional, their surfaces are underlain by flood deposits that mainly represent reworked and redeposited Savanna Terrace sediment. Eolian sand dunes are commonly present on the Bagley Terrace. The

Bagley Terrace appears to be the equivalent of the Kingston Terrace mapped by Bettis et al., (1996) for the reach of the Mississippi River between about Dubuque and Keokuk, Iowa. The vertical incision of the late Wisconsin age valley fill by relatively low sediment concentration waters that flowed from proglacial lakes between about 14,000 and 12,000 years B.P. extended at least 15-20 m or more below the level of the modern floodplain in the upper valley from Pool 11 northward (Brown Survey, 1932).

5.1.1 Soils

Most of the upper Mississippi River watershed beyond the limits of the late Wisconsin age glacial deposits are underlain by silt-dominated sediment derived from loess fall during the glacial periods (Ruhe, 1983; Leigh and Knox, 1994). Thickness of this silty sediment commonly range from 5 to 20 feet (2 to 7 m) along the margins of the Mississippi River and the Illinois River downstream of the big bend north of Peoria. Loess thicknesses of 30 feet (10 m) or more occur in east central Iowa. Figure 5-5 is a modified version of R.V. Ruhe's (1983, p. 131) map showing the thickness of loess deposited during the last glacial advance into the northern upper Mississippi river valley between about 25,000 and 12,000 radiocarbon years ago. The loess thickness ranges from few to several feet. The loess of the region commonly ranges from 65 or greater percent silt and is easily eroded. The abundance of loess and agricultural land use explains the high suspended sediment loads observed for the upper Mississippi River and many of its tributaries such as the Illinois River.

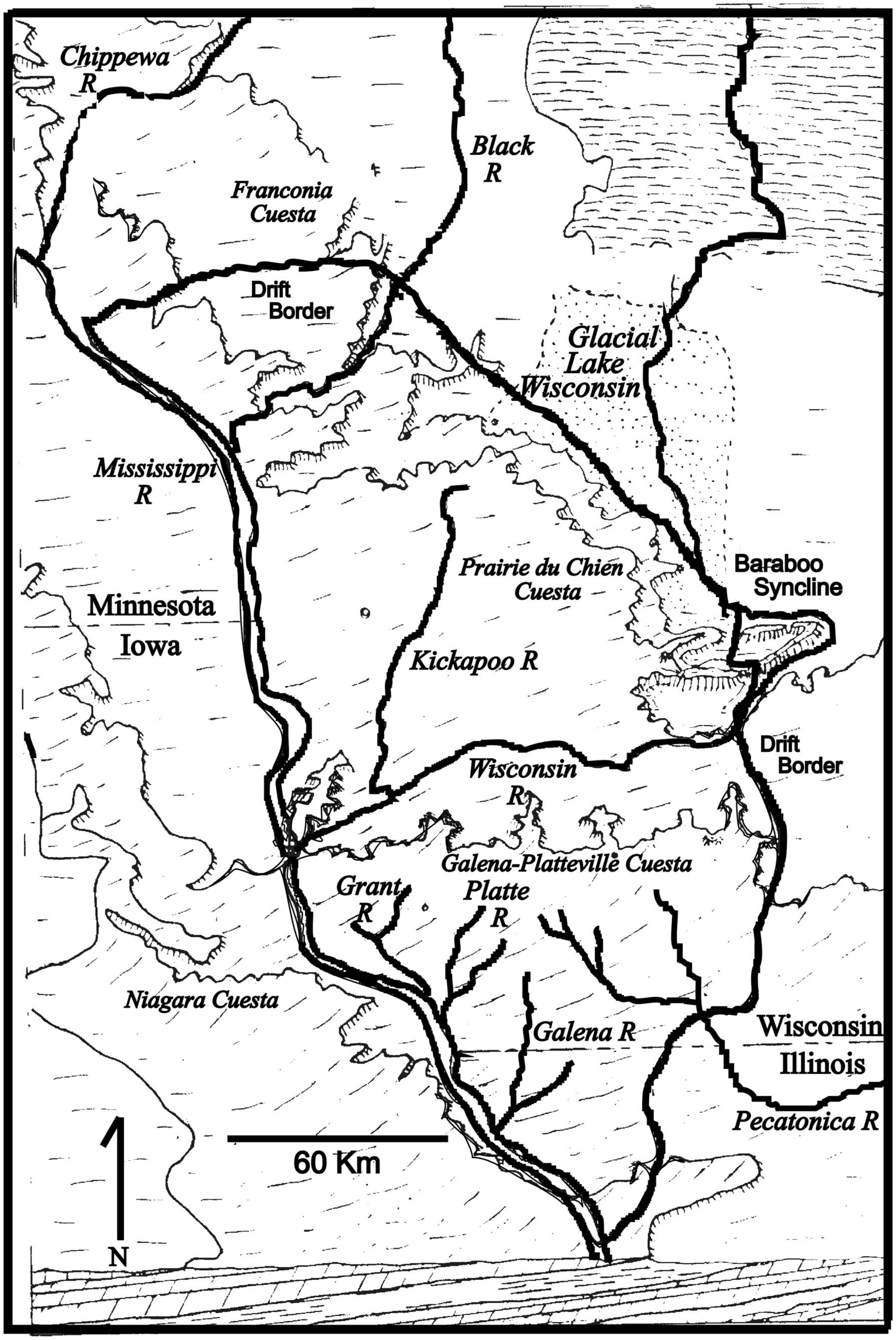


Figure 5-3: Narrow bedrock gorges characterize the Mississippi River where it crosses through bedrock cuestas (ridge lines) (Knox and Hudson, 1995).

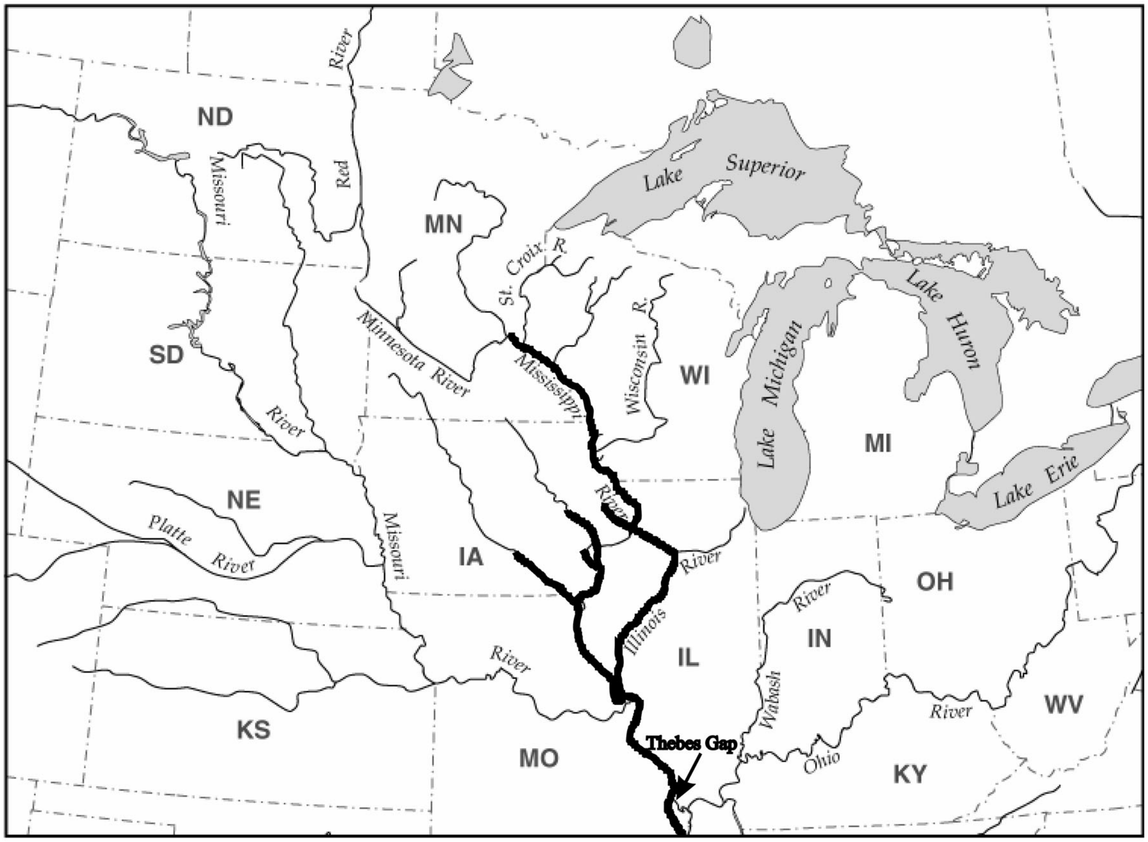


Figure 5-4: Prior to about 20,000 years B.P. the Mississippi River flowed southeastward across northwestern Illinois to join the present Illinois River near the big bend in north-central Illinois.

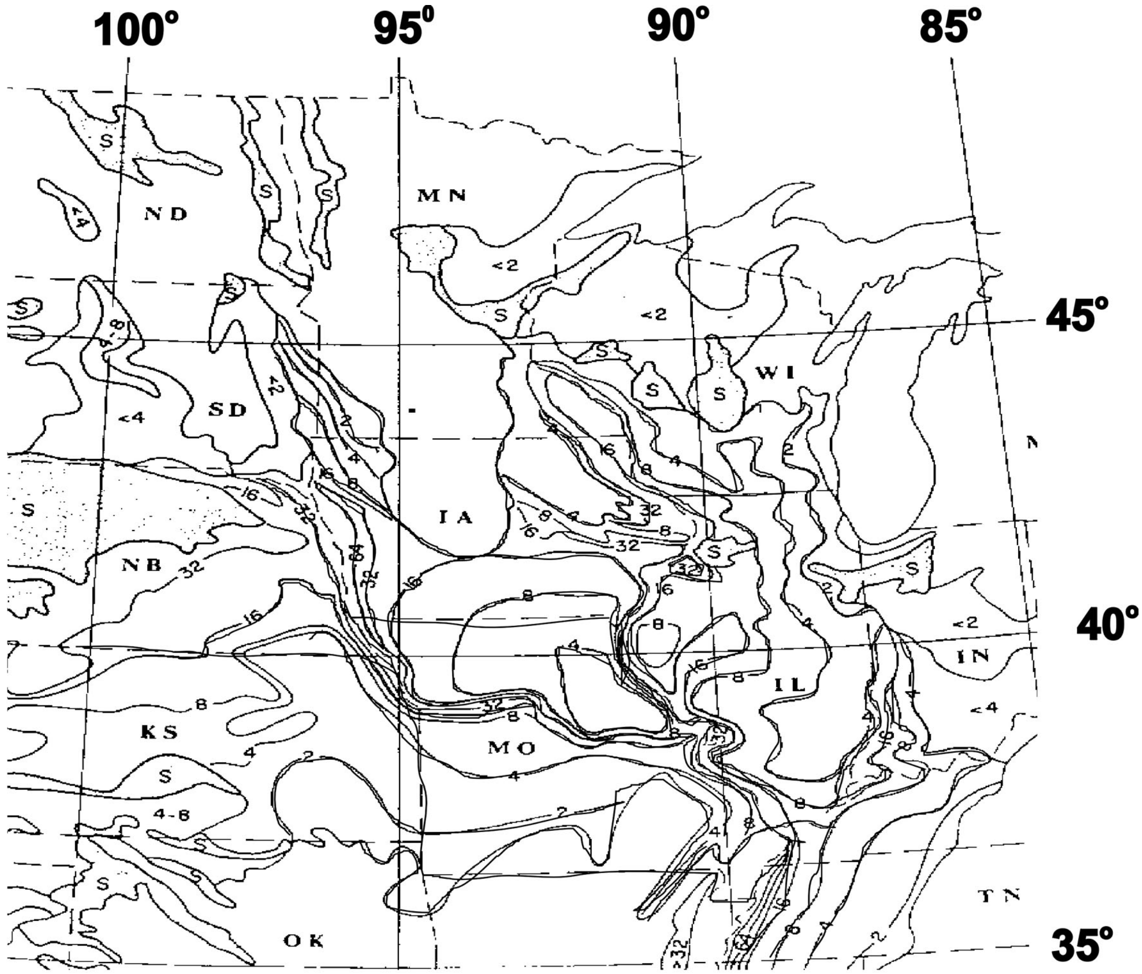


Figure 5-5: Loess thickness (ft) in the Upper Mississippi River basin (after Ruhe, 1983).

5.2 GEOMORPHIC REACHES

In this section, reaches of similar geomorphic characteristics along the Upper Mississippi River and Illinois Waterway are defined. The geomorphic reaches were identified based on one or more distinct characteristics related to valley and floodplain morphology, locations of geologic controls, gradient properties of the longitudinal profile, and sediment transport characteristics. The definition of geomorphic reaches assists in understanding the existing physical conditions of the river system, underlying geologic and hydrologic controls, and possible future conditions of the river systems.

5.2.1 Upper Mississippi River

The longitudinal profile of the upper Mississippi River can be divided into at least the following ten major Geomorphic Reaches (Figure 5-2). The limits of the reaches are defined as:

Geomorphic Reach 1: Pools 1-3
Geomorphic Reach 2: Pool 4 (Lake Pepin)
Geomorphic Reach 3: Pools 5 – 9
Geomorphic Reach 4: Pools 10 – 13
Geomorphic Reach 5: Pools 14 - 17
Geomorphic Reach 6: Pools 18 - 19
Geomorphic Reach 7: Pools 20 – 22
Geomorphic Reach 8: Pools 24 – 26
Geomorphic Reach 9: Below Pool 26 to Thebes Gap
Geomorphic Reach 10: Thebes Gap to Ohio River confluence

Following is a detailed discussion of the characteristics of each reach:

Geomorphic Reach 1. This reach includes Pools 1 through 3 and represents the area upstream of Lake Pepin. The reach includes numerous terrace remnants of the Bagley Terrace complex. Bed load from the upper Mississippi River is gradually extending a delta into Lake Pepin at the downstream end of the reach. Much of the sediment in the floodplain of Pools 2 and 3 accumulated by prograding of a post-glacial delta in the former upstream end of Lake Pepin (Ojakangas and Matsch, 1982, p. 113). Lake St. Croix at the mouth of the St. Croix River originated after about 9,500 radiocarbon years ago when Mississippi River sedimentation began blocking flow from the St. Croix River (Eyster-Smith et al., 1991). Since an age of 9,500 radiocarbon years equates to approximately 10,500 calendar years (Stuiver and Reimer, 1993), the average post-glacial rate of Mississippi River delta progradation is about 25 ft/yr (7.6 m/yr), given that post-glacial shortening of the lake is about 50 miles (80 km) (see below – Geomorphic Reach 2).

The modern short-term rate of valley alluviation and floodplain emergence probably is much smaller than 7.6 m/yr as shown by comparison of land and water areas on the Brown Survey maps versus recent aerial photography. The high magnitude long-term average rate results from the abundance of easily eroded and transportable sediment that was available during the early post-glacial period. However, isolated sections of the Lake Pepin delta are continuing to advance at high magnitude rates. A comparison of recent photography against 1940 photography of the delta area showed the active edge of the delta had prograded about 9000 ft (2,750 m) in the last half century. This locally specific rate represents an impressive 184 ft/yr (56 m/yr). Corps of Engineers cross section surveys show relatively modest to little sedimentation in lower Lake Pepin since the 1970s, suggesting that much of the sediment load is being deposited in upstream delta formation and that the remainder of the load is largely being transported through the system.

Geomorphic Reach 2. Reach 2 is represented by Pool 4 and Lake Pepin. Lake Pepin is a post-glacial lake that formed when the Chippewa River built a large alluvial fan into the Mississippi River beginning not later than about 9,000 radiocarbon years ago (Ojakangas and Matsch, 1982, p. 113). Much of the Chippewa alluvial fan probably accumulated during early post-glacial time following the deep incision of the mainstem Mississippi River by runoff from proglacial lakes. A radiocarbon age of 9,000 years B.P. is approximately 10,000 calendar years ago and equates to an age of about 8,000 B.C. (Stuiver and Reimer, 1993). Ojakangas and Matsch (1982, p. 113) report that Lake Pepin once extended upstream as far as St. Paul, but a post-glacial delta formed by sediment derived from the Minnesota and upper Mississippi Rivers has advanced downstream shortening the length of the lake by 50 miles (80 km).

Geomorphic Reach 3. This relatively steep reach is dominated by the enormous sandy bed load contributed by the Chippewa River and to some extent the Black River (Rose, 1992). The reach includes Pools 5 through 9. As seen from historic mapping, prior to the locks and dams closure, this reach exhibited classic island-braided morphology. On a per pool basis, Pools 7 through 10 have either the highest or are among the highest total absolute acreage of islands in the Upper Mississippi River system (Figure 5-40). Terraces are common along the valley margins. The Mississippi River valley narrows in the downstream direction through this reach, especially south of LaCrosse, WI, where resistant dolomite rock formations replace the less resistant sandstone formations characteristic of valley walls farther upvalley. Longitudinal gradient flattening in lower Pool 9 appears to be related to the effects of the Wisconsin River alluvial fan which is located in Pool 10 (Figure 5-2). Certain tributaries in the sandstone region of western Wisconsin, such as the Buffalo River, experienced major gully erosion from the 1890s to 1940s. The deposits from these gullies were largely stored in the watershed as alluvial fans. Improved land use of recent years has reduced erosion rates providing an excess sediment transport capacity, causing the remobilization of the sediments stored on the downstream alluvial fans (Knox and Faulkner, 1994).

Geomorphic Reach 4. Reach 4 includes Pools 10 through 13 and represents an extended valley segment for which the valley walls are dominated by very erosionally resistant limestone and dolomite formations. The acreage of islands for both pre- and post locks and dams construction is very low for Pools 11 through 13, in large part because the valley is confined to a very narrow bedrock gorge. The narrow gorge begins at the downstream edge of the Wisconsin River mouth where the Galena-Platteville Cuesta is crossed by the Mississippi River (Figure 5-3). The narrow gorge extends to the southern margin of the Driftless Area in northwestern Illinois in the upper reach of Pool 13 (Figure 5-3).

The pre-locks and dams low water gradient of this reach was less steep than the pre-locks and dams low water gradient for much of upper Reach 3, especially from Lower Pool 4 through Pool 8. Pool 10 is dominated by the influence of a large alluvial fan caused by deposition of abundant sandy bed load at the mouth of the Wisconsin River. Rose (1992) estimated that the lower Wisconsin River at the Muscoda gage site is transporting 49 percent of its total sediment load as bed load. The fan produces a slight hump in the longitudinal profile of the Mississippi River and causes the Mississippi River to experience a slight flattening of its gradient on the upstream margin of the fan. The major reduction in valley width in conjunction with bedrock geology and the forest covered alluvial fan extending into the Mississippi River at the Wisconsin River mouth produces an important hydraulic backwater effect on the upstream Mississippi River in upper Pool 10. Downstream, a slight steepening of the Mississippi alluvial gradient occurs on and down valley of the Wisconsin River alluvial fan.

Radiocarbon dating by Knox (1998) (Lab # BETA-92063) for an island in upper Pool 10, on the upstream margin of the Wisconsin River alluvial fan, showed that the island aggraded at an average rate of about 0.07 cm/yr since about 700 BC. Radiocarbon dating by Knox (unpublished) (Lab # BETA-92065) for a floodplain site weakly influenced by alluvial fan sedimentation in lower Pool 10 on the downstream margin of the Wisconsin River alluvial fan, showed a long-term average rate of aggradation of about 0.13 cm/yr since about 1960 BC. The higher rate downstream probably reflects alluvial fan sedimentation. Overstreet and Kolb (1994, p. 96-98) obtained ages of about 3400 BC and about 4100 BC for shell midden material buried at respective depths of about 1.80 m and 2.25 m below the present ground surface along the west shore of McGregor Lake in Pool 10. The ages suggest respective sedimentation rates of 0.03 cm/yr and 0.04 cm/yr. The lower rates along McGregor Lake shoreline may reflect resuspension and erosion of sediment there compared to the island levee and fan environments. Nevertheless, all of the rates presented here are consistent with the idea of Mississippi River long-term post-glacial progressive aggradation as stored sediment in tributaries is reworked and transported into the main valley.

Examination of Corps of Engineers cross valley surveys completed since dam closure on Pool 11 show that this pool has experienced up to 8 ft (2.4 m) of main-channel sedimentation in the lower pool. A general leveling of backwater topography due to sedimentation has also occurred (see also discussion in Section 5.6.2.1). The more significant magnitude of sedimentation is probably due to several moderate size tributaries (Platte, Grant, Little Maquoketa, and Turkey Rivers) flowing into the narrow confines of Pool 11. Each of these tributary watersheds drains intensely cultivated watersheds with uplands that are underlain with relatively thick deposits of easily eroded loess sediment (Figure 5-5).

Geomorphic Reach 5. Reach 5 involves Pools 14 through 17. Pools 14 and 15 represent a very steep reach through a gorge incised by Illinoian and late Wisconsin age glacial meltwater when blockage of the ancient Mississippi River drainage occurred in north-central Illinois. Downstream, in Pool 16, the Mississippi River continues to flow between valley walls constrained by bedrock, but this segment of the valley probably has greater antiquity than the segment in Pools 14 and 15 (Horberg, 1950, p. 48-49). Consequently, large islands have evolved in the Pool 16 segment of flatter gradient and somewhat greater valley width. These islands probably are at least partially due to sediment deposition from flow expansion and velocity reduction below the narrows of Pool 15. Downstream of Muscatine, Iowa in Pool 17, the Mississippi River enters the ancient pre-glacial Iowa River valley where the valley width becomes exceptionally wide. The wide floodplain promotes flow expansion, velocity reduction, and contributes to extensive island development here. It is also noteworthy that islands in this reach have large quantities of historical overbank sedimentation (Personal communications with Anderson, 1997), a situation that has not been common in the other upstream reaches described above.

Geomorphic Reach 6. Reach 6 consists of Pools 18 and 19. The pre- locks and dams water surface gradients of lower Reach 6 in Pool 19 are relatively steep and result from this segment of the valley coinciding with a geologically young rock gorge between Fort Madison and Keokuk (Figure 5-2). The flow diversions of glacial meltwaters that contributed to the formation of this gorge occurred during the Illinoian Stage of glaciation 300,000 to 130,000 years ago and probably also during pre-Illinoian glaciation in the area (Johnson, 1986; Willman and Frye, 1970).

Geomorphic Reach 7. Reach 7 involves Pools 20 through 22. The gradient of this reach is surprisingly steep considering that this valley segment is coincident with a segment of the ancestral Iowa River valley. The steepness may be partially a consequence of the large sediment load delivered to the reach by the Des Moines River which joins the Mississippi River just below Lock and Dam 19 at Keokuk. The reach includes evidence of old meander belts and extensive deposits of post-glacial alluvium, suggesting that lateral channel adjustments have been active here.

Geomorphic Reach 8. Reach 8 includes Pools 24 through 26. Reach 8 shows the upstream backwater influence of the alluvial fans at the mouths of the Missouri and Illinois Rivers. Because the Illinois River is dominated by suspended sediment load, and the Missouri River has traditionally introduced an enormous bed load contribution, the hump in the Mississippi River longitudinal profile near Lock and Dam 26 probably has resulted mainly from sedimentation contributed by the Missouri River.

Geomorphic Reach 9. This reach begins the Open River section of the UMR, below Lock and Dam 26, and extends downstream to Thebes Gap (Figure 5-2 and Figure 5-4). The head of the reach is especially steep because it includes the dominating influence of the Missouri River alluvial fan. The 1930s low water gradient was actually steeper than the 1930s low water gradient on Reach 2 extending downstream on the Chippewa alluvial fan. Meade et al. (1990) reported that after closure of the five large dams on the Missouri River between 1953 and 1963, the flow of sediment from the upper Missouri River basin virtually stopped. Erosion of sediment from channel margins of the Missouri River downstream of the dams has partially maintained sediment delivery to the Mississippi River, but the load is much reduced from pre-dam magnitudes which could accelerate erosion condition downstream.

Geomorphic Reach 10. Reach 10 extends from the rock gorge at Thebes Gap to the confluence with the Ohio River, near Cairo, Illinois. The age of the river through Thebes Gap is relatively young, dating from not older than about 14,000 to 15,000 radiocarbon years ago (Willman and Frye, 1970, p. 35), and probably dates from about 11,700 to 10,800 radiocarbon years ago (Royall et al., 1991; Porter and Guccione, 1994). Its diversion through the gap occurred in response to a large flood caused by the rapid drainage of a glacial lake at the retreating margin of the continental glacier. The gradient of the river is relatively steep below the Thebes Gap rock gorge due to the rock control in the gorge.

5.2.2 Illinois Waterway

The longitudinal profile of the Illinois Waterway can be divided into at least two geomorphic reaches. The limits of the reaches are approximately defined by the diversion of the Mississippi River into the Illinois River basin during past periods of glaciation. The general characteristics of each reach are described as follows:

Geomorphic Reach 1. Reach 1 involves Dresden, Marseilles and Starved Rock Pools. Upstream of Dresden Pool the location and condition of the waterway has been generally defined by human actions so geomorphic influences along the reach are relatively small. The pools in Reach 1 are much steeper than the average slope for the UMR as is seen in Figure 5-19. The average length of the three pools is relatively short, about 18.3 miles. The main channel widens upstream of both Dresden and Starved Rock locks and dams due to water impoundment. However, throughout most of the reach, the river is primarily confined to the main channel. Only small portions of the reach are classified as backwaters.

Geomorphic Reach 2. Reach 2 involves the three downstream most pools, Alton, LaGrange and Peoria. The conditions of the reach are the direct result of the geologic history of the waterway. As is discussed in Section 5.1, successive glaciations have redirected the course of Mississippi River several times. Until about 20,000 years ago during the late-Wisconsin age of glaciation the Mississippi River flowed across northwestern Illinois and joined the present-day Illinois River at the upstream end of Reach 2. Therefore, the IWW Reach 2 occupies the ancient course of the Mississippi River and this accounts for much of the low gradient and large valley widths that are characteristic of this reach. The three pools are very long, each about 70 to 80 miles in length. As seen in Figure 5-18, the pools in this reach are about twice the length of the longest pool on the UMR (Figure 5-17). The channel gradient through the reach is very flat, much flatter than the average slope of the UMR (Figure 5-19). The backwater from Lock and Dam 26 on the UMR influences the Alton Pool. The main channel for the reach is relatively narrow and uniform with some slight increase in its width upstream of the dams. The only significant main channel widening is in Lake Peoria. The backwater areas along the reach are in many cases well-defined areas away from the main channel and may or may not have direct hydraulic connection to the main channel.

5.3 SEDIMENT TRANSPORT

The geomorphic conditions of the UMR and IWW are dependent on sediment supply and sediment transport. Erosion and deposition of sediment along a channel influences the formation and evolution of aquatic areas. Variations between the supply of sediment and sediment transport capacity determines whether erosion or deposition will occur. The relative stability of a fluvial system, the potential for erosion or sedimentation, and future geomorphic conditions can be assessed by investigation of sediment transport conditions. In the following sections, the sediment characteristics along the UMR and IWW are described and estimates of sediment transport are developed.

5.3.1 Bed Material Characteristics

Sediments found in appreciable quantities in the bed of a watercourse are referred to as bed material. The size of bed material sediments is important because it influences the manner that they are transported along the watercourse and their potential for erosion or deposition. Available bed material data for the UMR and IWW were collected and summarized. The characteristics of bed material were reviewed to understand the sources of sediment, the involved sediment transport processes, and the historic and potential future geomorphic changes along each watercourse.

5.3.1.1 Upper Mississippi River

Bed material characteristics of the UMR were identified from the database of information previously described in Chapter 2. The available data consists primarily of studies and data sets for specific navigation pools along the UMR. A summary of the available pool-specific data sources is shown in Table 5-1. The sediment characteristics provided by the available literature ranges from complete size gradation analysis results to the relative percentage of sand, silt, and clay. Maps showing the locations at which bed material samples have been taken in each pool are presented in Appendix D.

One set of bed material size data that provides comprehensive coverage of the main channel throughout the entire UMR study reach was developed by the USACE Waterways Experiment Station (Seal, 1997). The data set includes size gradation information for samples taken along main channel transects located at five mile intervals along the UMR and IWW. Along the UMR, the available data cover the reach from just upstream of Lock and Dam No. 26 (RM 210) to immediately downstream of Lock and Dam No. 3 (RM 790). However, only data for every other sampling transect, ten mile intervals, was available for use in the current study. The data identifies sediment grain sizes for which 95, 84, 65, 50, 35, 30, 16, and 5 percent of the sediment is finer, by weight. The data set does not define sediment characteristics for backwater areas. It is also noted that bed material data was collected as part of a streambank erosion study for the UMR (USACE, 1997). This data set was not evaluated for the current study as samples were only taken at locations of recognized bank erosion at the time of the study. Hence, the data set may not be representative of typical conditions along the river.

Table 5-1: Summary of pool-specific bed material data sources.

Pool #	Reference	Sample Date	Sample Size	Data Type	Comment	Sample Location Map
1	USGS, 1997	1991	12	TS*	From downstream 1/3 of pool.	
2	USGS, 1997	1991	18	TS*	From downstream 1/3 of pool.	
	USGS, 1997	1991	18	TS*	From downstream 1/3 of pool.	
	USGS, 1997	1992	18	TS*	From downstream 1/3 of pool.	
3	USGS, 1997	1991	16	TS	From downstream 1/3 of pool.	
4	McHenry et al., 1978a	1977	11	SSC	Lake Pepin sedimentation studies.	Plate D-1
	Bhowmik et al., 1992	1989	15	D,G	UMR near Red Wing, MN (RM 788-789)	
	USGS, 1997	1991	15	TS*	From upper Lake Pepin.	
	USGS, 1997	1991	21	TS*	From lower Lake Pepin.	
5	USGS, 1997	1991	18	TS*	From downstream 1/3 of pool.	
5A	USGS, 1997	1991	14	TS*	From downstream 1/3 of pool.	
6	USGS, 1997	1992	20	TS*	From downstream 1/3 of pool.	
7	McHenry and Ritchie, 1978	1975	6	SSC	Lake Onalaska sediment accumulation study.	Plate D-2
	McHenry and Ritchie, 1978	1977	15	SSC	Lake Onalaska sediment accumulation study.	
	USGS, 1997	1991	20	TS*	Lake Onalaska.	
8	McHenry et al., 1978b	1975	6	SSC	Pool 8 sediment accumulation study.	Plate D-3
	McHenry et al., 1978b	1977	18	SSC	Pool 8 sediment accumulation study.	
	USGS, 1997	1991	20	TS*	From downstream 1/3 of pool.	
	USGS, 1997	1991	15	TS*	From downstream 1/3 of pool.	
	USGS, 1997	1992	20	TS*	From downstream 1/3 of pool.	
9	McHenry and Ritchie, 1977	1976	39	SSC	Pool 9 sediment accumulation study.	Plate D-4
	USGS, 1997	1991	18	TS*	From downstream 1/3 of pool.	
10	USGS, 1997	1991	20	TS*	From downstream 1/3 of pool.	
11	Nakato, 1983	1983	42	D	Preconstruction study near RM 614.	Plate D-5
	Toda and Nakato, 1987	1985	4	G	Post construction study near RM 614.	
	USGS, 1997	1991	20	TS*	From downstream 1/3 of pool.	
12	USGS, 1997	1992	20	TS*	From downstream 1/3 of pool.	
13	USGS, 1997	1991	20	TS*	From downstream 1/3 of pool.	
14	USGS, 1997	1991	16	TS*	From downstream 1/3 of pool.	
15	USGS, 1997	1992	18	TS*	From downstream 1/3 of pool.	
16	USGS, 1997	1991	19	TS*	From downstream 1/3 of pool.	
17						
18	USGS, 1997	1992	18	TS*	From downstream 1/3 of pool.	
19	Adams, 1993	1982	51	SSC	Bed material characteristics in Pool 19.	Plate D-6
	Adams, 1993	1982	52	d50	Bed material characteristics in Pool 19.	
	Adams, 1993	1983	3	SSC, D	Bed material characteristics in Pool 19.	
	Adams, 1993	1984	130	SSC, D	Bed material characteristics in Pool 19.	
	Adams, 1993	1985	41	SSC, D	Bed material characteristics in Pool 19.	
	Adams, 1993	1986	16	SSC, D	Bed material characteristics in Pool 19.	
	USGS, 1997	1991	23	TS*	From downstream 1/3 of pool.	
20	Nakato and Kennedy, 1977	1976	143	L	Field study of sediment transport.	Plate D-7
	Nakato and Vadnal, 1981	1978	114	TS	Field study and sediment transport model test.	
	USGS, 1997	1991	12	TS*	From downstream 1/3 of pool.	
21	USACE, 1987	1985	9	SSC,d50	Sedimentation report for Quincy Bay.	
	USGS, 1997	1992	19	TS*	From downstream 1/3 of pool.	
22	USGS, 1997	1991	21	TS*	From downstream 1/3 of pool.	
24	USGS, 1997	1991	18	TS*	From downstream 1/3 of pool.	
25	USGS, 1997	1992	19	TS*	From downstream 1/3 of pool.	
26	Goodwin and Masters, 1983	1980	239	d50	Sedimentology and bathymetry of Pool 26.	Plate D-8
	Molinas, 1983	1982	1	G	Application of streamtube computer model.	
	Simons et al., 1987	1985	2	TS*	Effect of tow boat traffic.	
	Simons et al., 1987	1987	1	TS*	Effect of tow boat traffic.	
	USGS, 1997	1991	13	TS*	From downstream 1/3 of pool.	
OR						

LEGEND

SSC - Percent Sand, Silt and Clay
D - Table of sediment diameter for various percent finer.
G - Graph of particle size distribution
TS - Tabulation of sieve analysis results
d50 - Table of d_{50} values
L - Lateral distribution of d_{50} values

* Samples composited
Note: Sample location maps w/data are located in Appendix D.

The variation of sediment sizes along the UMR navigation channel is shown in Figure 5-6. The sediment size at which 16 (D_{16}), 50 (D_{50}), and 84 (D_{84}) percent of the total sediment distribution is finer is shown on the figure. As seen from data, upstream of the Des Moines River (RM 361) the channel sediments are almost totally comprised of sand-sized (0.0625 mm to 2 mm) or finer material. Between the Des Moines River and Lock and Dam No. 26, the D_{84} and D_{50} sediment sizes include up to gravel-sized material.

Figure 5-7 shows the median sediment size (D_{50}) of samples taken along the navigation channel within the lower, middle, and upper third of each pool along the UMR. Sediments in the middle, and upper third of the pool are characteristically coarser than the sediments in the lower third of each pool. Figure 5-8 depicts the variation in median particle size within the main channel, but outside of the navigation channel, in the lower third of each pool along the UMR. The sediments in this portion of each pool are characteristically comprised of very fine and fine sand (0.0625 mm to 0.25 mm). Almost all samples represent sand-sized material (.0625 mm to 2 mm).

Only limited sediment grain size data is available for backwater areas along the UMR. A summary of bed material size data for various aquatic areas along the UMR was prepared. The median sediment size determined for the main channel, contiguous backwater areas, and secondary channels in various pools is shown in Figure 5-9. The limited data in the figure (Pools 11, 19, 20 and 26), shows little variation in the average sediment size can be discerned between the various aquatic areas sampled. The sediments are all characterized as fine to medium sand-sized material.

The Rock Island District samples bed material in the spring of each year at potential dredging sites. Dredging may or may not take place at these sites. These data are presented in Figure 5-10 for the time period from 1990 to 1999. The median size for the majority of the samples is between 0.1 and 2 mm, which is approximately the range for sand. A few of the samples are larger, in the range of fine to medium gravel, but none of the samples are finer than sand. No significant difference in sediment sizes is observed between the right and left bank.

5.3.1.2 Illinois Waterway

The USACE Waterways Experiment Station data set (Seal, 1997) also contains sediment size gradation data for the IWW. Information was available for channel transects located at ten mile intervals along the IWW. The available data extend along the IWW from RM 1.0 to just below Dresden Lock and Dam (RM 270). The data identifies sediment grain sizes for which 95, 84, 65,50, 35, 30, 16, and 5 percent of the sediment is finer, by weight. The data set does not define sediment characteristics for backwater areas.

The variation of sediment sizes along the IWW navigation channel is shown in Figure 5-11. The sediment size at which 16 (D_{16}), 50 (D_{50}), and 84 (D_{84}) percent of the total sediment distribution is finer is shown on the figure.

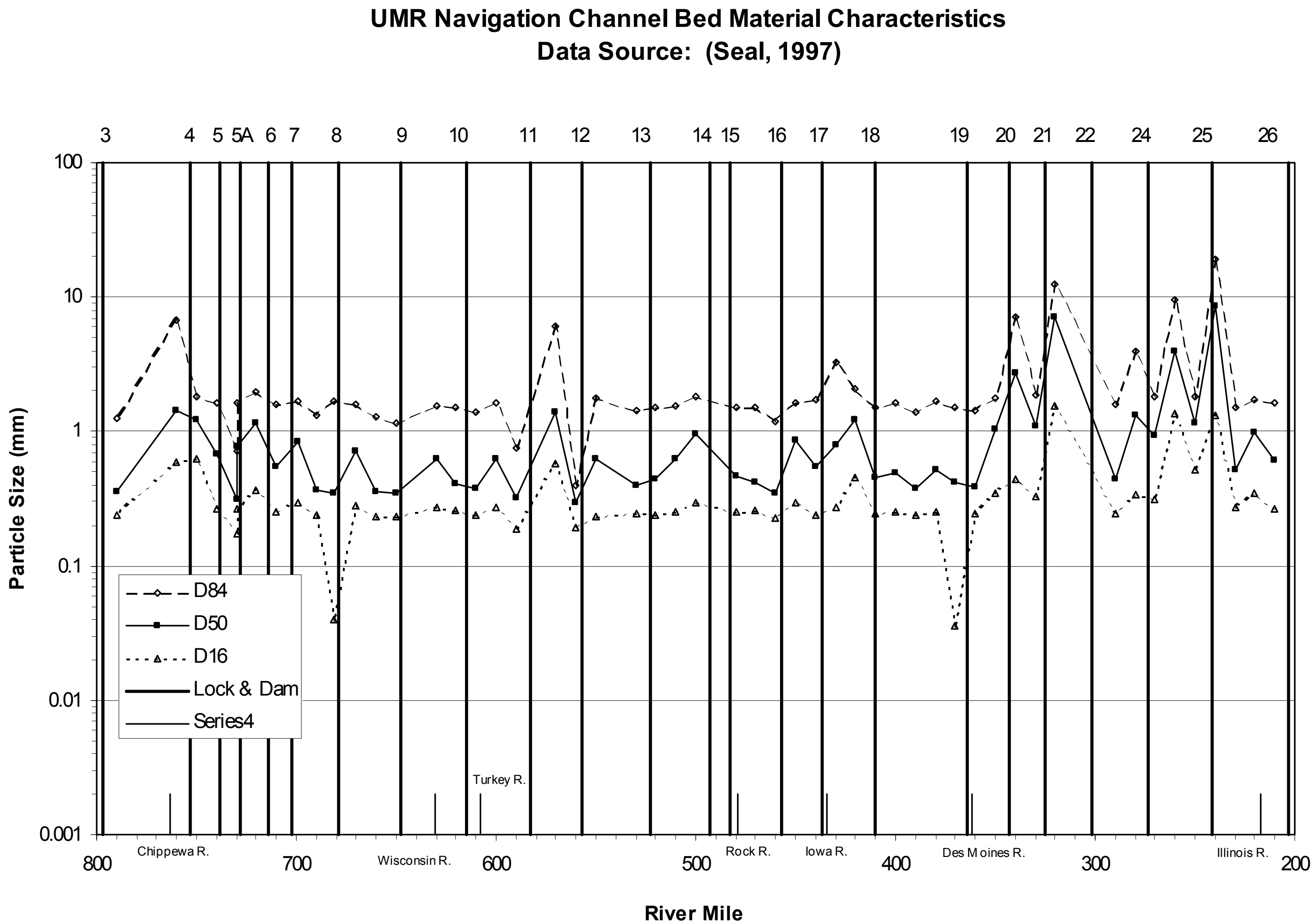


Figure 5-6: Variation of D_{16}, D_{50}, and D_{84} sediment sizes along the UMR Navigation Channel.

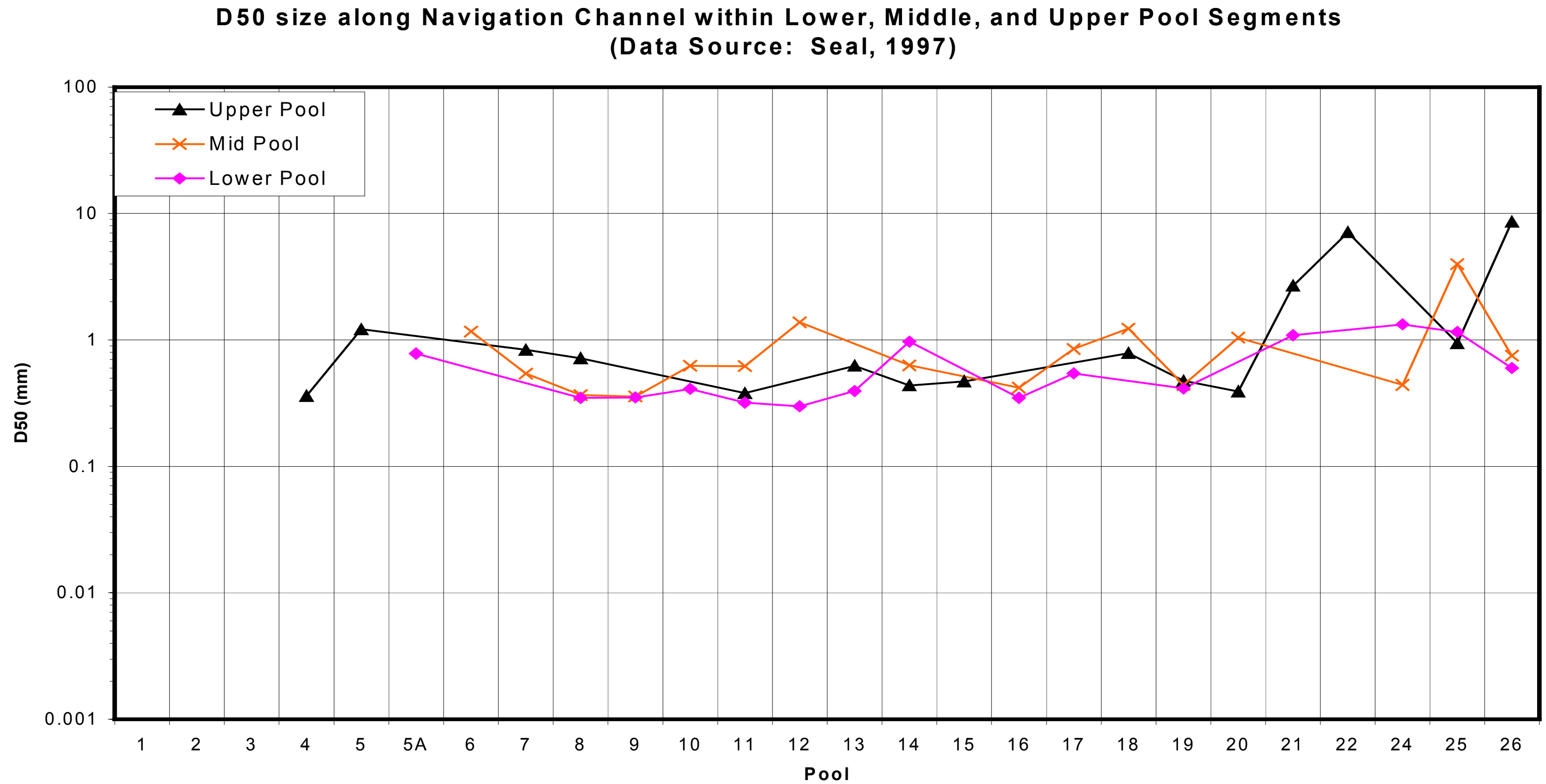


Figure 5-7: Variation of median sediment size (D_{50}) along the UMR Navigation Channel within the lower, middle, and upper third of UMR navigation pools.

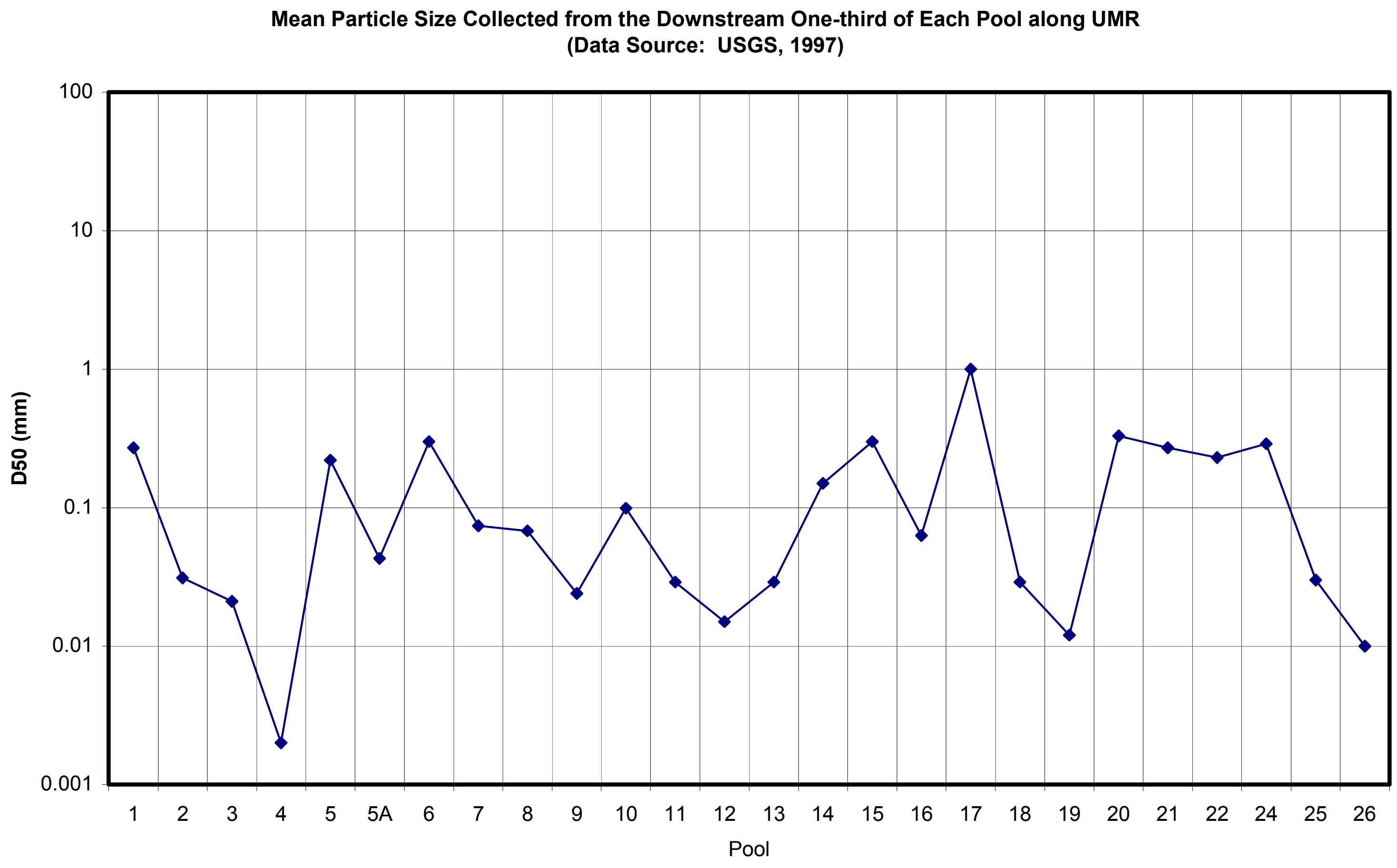


Figure 5-8: Variation in median particle size (D_{50}) in the lower third of each pool, in the main channel and outside of the main channel.

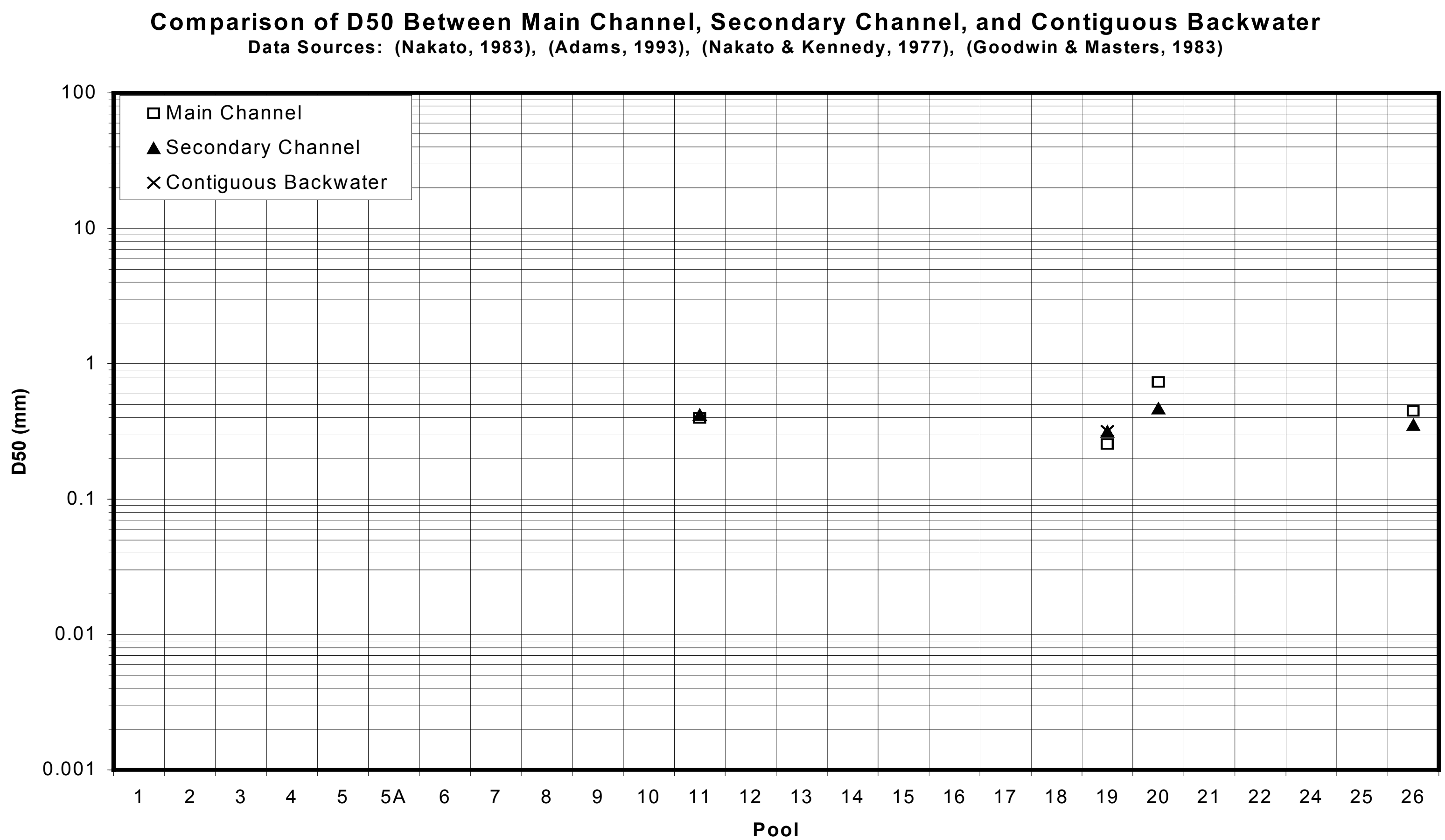


Figure 5-9: Comparison of median sediment size in main channel, secondary channels, and contiguous backwater areas along the UMR.

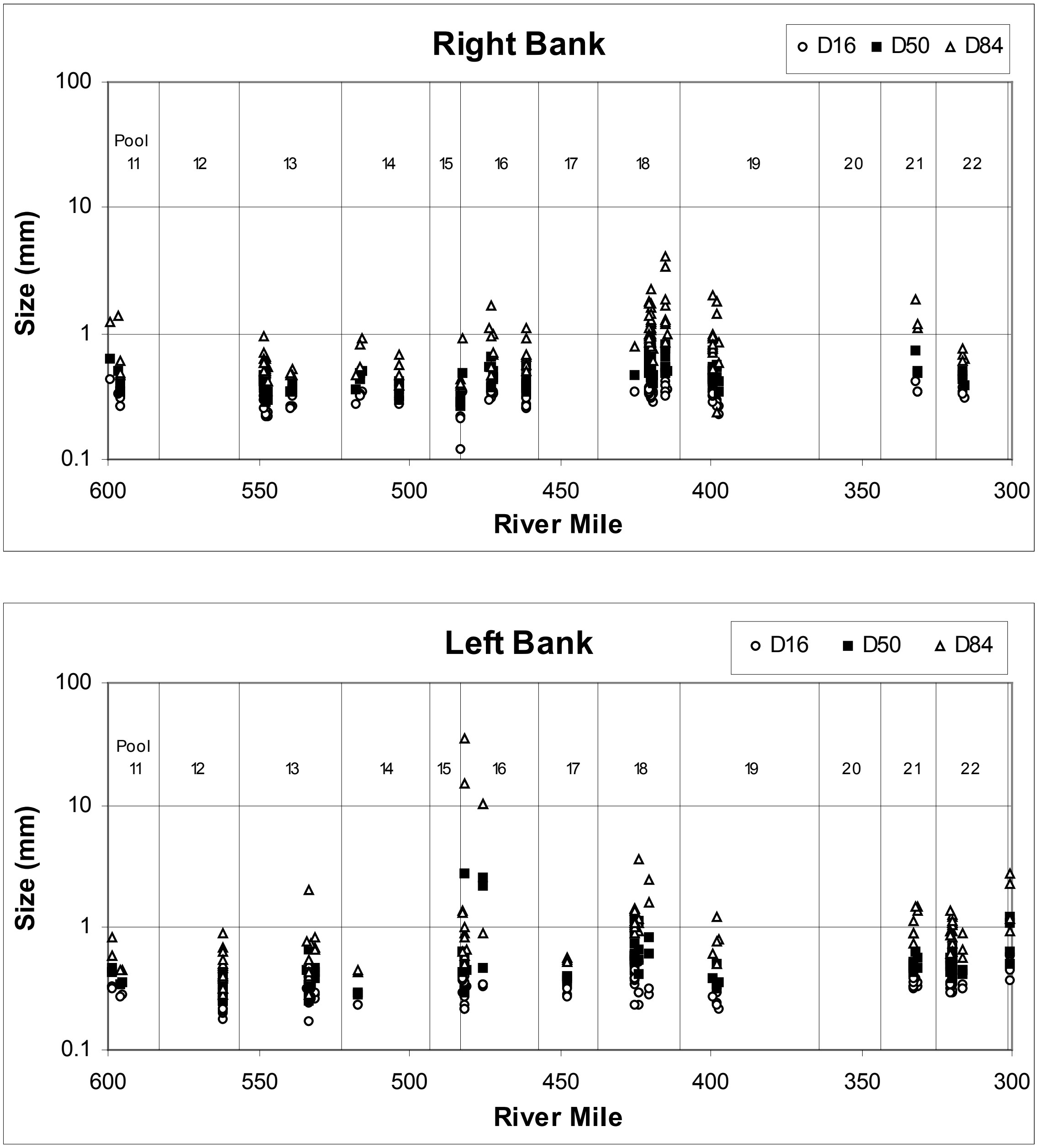


Figure 5-10: Sediment samples at potential dredge sites in the Rock Island District from 1990 to 1999 (Source: Rock Island District).

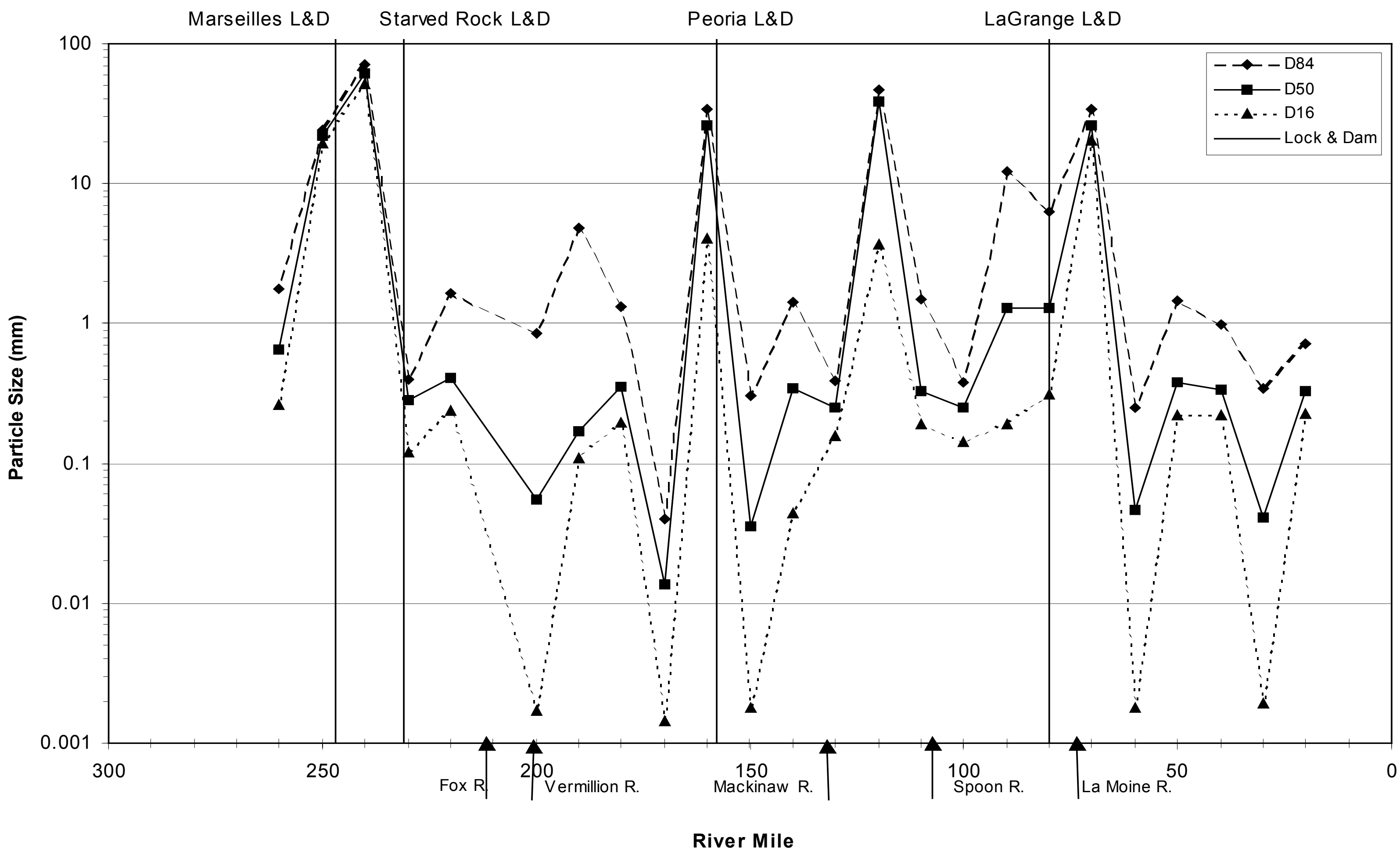


Figure 5-11: Sediment gradation characteristics along the IWW navigation channel (Source: Personal Communication with Seal 1997).

In comparison to sediments along the UMR navigation channel (Figure 5-6), the sediments along the IWW navigation channel show a much greater level of variability. Whereas the majority of sediments along the UMR were sand-sized, the IWW has sediments which range from gravel- to silt-sized materials. Furthermore, the UMR exhibits a distinct coarsening of sediment size downstream of the Des Moines River confluence whereas the IWW was seen to be generally variable in sediment size throughout its length.

5.3.2 Sediment Transport Estimates

Sediment is transported along a watercourse in one of three ways: 1) suspended in the flow, 2) rolling or sliding along the channel bed, or 3) saltation (jumping). Sediment transport is usually divided into bed load and suspended load. Bed load refers to the sediments moving by saltation, rolling, or sliding in the zone immediately above the channel bed. Suspended load refers to sediments, transported by turbulent currents, that stay in suspension for an appreciable length of time. The suspended load includes wash load, particle sizes finer than those represented in significant quantities in the bed of the channel. Typically, wash load is comprised of silt- and clay-sized particles that seldom come out of suspension but is 'washed' through the system.

The relation of sediment supply and sediment transport capacity governs the potential for sediment erosion and deposition along a watercourse. Estimates of sediment transport can be used to define sediment supply from tributaries and transport capacity along the mainstem. A sediment budget for the fluvial system can also be developed from sediment transport estimates. A sediment budget defines the relative magnitude and importance of the sources and sinks of sediment within the fluvial system. In the following sections, the development of sediment transport estimates for the UMR and IWW is described.

5.3.2.1 Upper Mississippi River

Available sediment transport data were collected and evaluated to develop estimates of the average annual total sediment load transported along the mainstem UMR and its tributaries. The total sediment load is comprised of two parts, the suspended load, and the bed load. Field measurements of suspended sediment transport were used to develop the total load estimates. Typically, only measurements of the suspended load are made. Measurements of bed load transport are difficult to make and typically unavailable. Bed load is commonly estimated as a fraction of the total load. In the following sections, the procedures used to develop the total sediment transport load estimates are described.

Suspended Load Transport Estimates

Suspended-load transport of material coarser than silt increases upstream from Lock and Dam 26. The percent of suspended sediment finer than sand (0.062 mm) measured from suspended sediment samples at various points along the UMR is shown in Table 5-2. As seen from the table, the percentage of suspended sediment finer than 0.062 mm (lowest limit of sands) increases in the downstream direction. A high percentage of silt- and clay-sized materials (finer than 0.062 mm) is transported in suspension at East Dubuque, Burlington, Keokuk, and Hannibal. It can be concluded that wash load dominates suspended load transport at these measurement stations.

Estimates of average annual suspended sediment transport along the Mississippi River and its tributaries were identified from available suspended sediment transport measurement records and previous studies. The United States Geological Survey (USGS) and the USACE have measured water and suspended sediment discharge at various locations within the UMR study area for varying periods of time. Except for four locations, the available records of the suspended load measurements used in this study were compiled by the USACE, Rock Island District. Records for the other four locations were obtained directly from the USGS. In total, twelve measurement stations are located along the Upper Mississippi River (UMR) and twenty-two stations are located on tributaries. A summary of the records obtained for each measurement station is shown in Table 5-3.

Table 5-3 also includes information for each mainstem sediment measurement station, locks and dams, and tributary with suspended sediment measurements records along the UMR. The river mile (RM) and navigation pool associated with each feature is also identified. The estimated annual suspended-load discharge, the available record period, and the number of years used to obtain the annual average suspended load are also defined in the table. As seen in the table, the record period varied from station to station, ranging from one year for the St. Croix River to forty-five years for the UMR at St. Louis. As noted previously, in Section 3.2, about 15-20 percent of the total drainage area in the UMR study area is ungaged and no estimates of the sediment supply from those areas exist. The ungaged tributary area will somewhat underestimate the tributary sediment load to the UMR.

Table 5-2: Percentage of suspended sediment finer than 0.062 mm (Nakato, 1981b).

River	Station	River Mile (RM)	Percent Finer Than 0.062 mm
Mississippi River	L&D 4	752.8	56.5
Mississippi River	L&D 5	738.1	74.6
Mississippi River	L&D 5A	728.3	73.6
Mississippi River	L&D 6	714.2	68.1
Mississippi River	L&D 7	702.5	72.8
Mississippi River	L&D 8	679.1	82.8
Mississippi River	East Dubuque, IL	579.3	86.1
Mississippi River	Burlington, IA	404.1	89.0
Mississippi River	Keokuk, IA	363.9	99.4
Mississippi River	Hannibal, MO	301.2	97.5

Table 5-3: Summary of UMR sediment transport estimates.

River Mile	Pool	Station/Tributary/Location	Gage No.	Drainage Area (sq. mi.)	Annual Suspended Load (Q_s) Discharge (tons/year)	Q_s/Q_t Ratio	Annual Bed Load (Q_b) Discharge (tons/year)	Q_b/Q_t Ratio*	Annual Total Load (Q_t) Discharge (tons/year)	Total Tributary Q_t to Pool (tons/year)	Record Length (years)	Q_s Record Period	Q_s Estimate Source	Q_b/Q_t Estimate Source
865		Mississippi River at Anoka, MN	05288500	19,100	187,200	0.90	20,800	0.10	208,000		20	1976-1995	Nakato, 1998	Nakato, 1981a
854.1		St Anthony Falls L&D		19,680										
847.7	1	Ungaged Tributary Area		4										
847.7	1	L&D No. 1		19,684						0				
844	2	Minnesota River at Mankato, MN	05330000	16,200	1,328,300	0.90	147,589	0.10	1,475,889		28	1968-1995	Nakato, 1998	Nakato, 1981a
815.2	2	Ungaged Tributary Area		1,106										
815.2	2	L&D No. 2		36,990						1,475,889				
811.3	3	St. Croix R. at St. Croix Falls, WI	05340500	6,240	78,800	0.90	8,756	0.10	87,556		1	1982-1982	Nakato, 1998	Nakato, 1981a
796.9	3	Ungaged Tributary Area		1,940										
796.9	3	L&D No. 3		45,170						87,556				
763.4	4	Chippewa River near Pepin, WI		9,010	526,400	0.56	413,600	0.44	940,000		6	1974-1983	Rose, 1992	Rose, 1992
752.8	4	Ungaged Tributary Area		2,920										
752.8	4	L&D No. 4		57,100						940,000				
750.2	5	Zumbro River at Kellog, MN	05374900	1,400	233,800	0.90	25,978	0.10	259,778		7	1975-1981	Nakato, 1998	Nakato, 1981a
744	5	Whitewater River nr. Beaver, MN	05376800	271	94,700	0.90	10,522	0.10	105,222		7	1975-1981	Nakato, 1998	Nakato, 1981a
738.1	5	Ungaged Tributary Area		74										
738.1	5	L&D No. 5		58,845						365,000				
728.3	5A	Ungaged Tributary Area		260										
728.3	5A	L&D No. 5A		59,105						0				
725.7	6	Ungaged Tributary Area		95										
725.7	6	Mississippi River at Winona, MN	05378500	59,200	902,200	0.90	100,244	0.10	1,002,444	0	13	1975-1987	Nakato, 1998	Nakato, 1981a
714.2	6	Ungaged Tributary Area		830										
714.2	6	L&D No. 6		60,030						0				
710	7	Black River nr. Galesville, WI	05382000	2,080	157,890	0.57	119,110	0.43	277,000		4	1974-1983	Rose, 1992	Rose, 1992
702.5	7	Ungaged Tributary Area		230										
702.5	7	L&D No. 7		62,340						277,000				
693.7	8	Root River nr. Houston, MN	05385000	1,270	725,700	0.90	80,633	0.10	806,333		9	1973-1981	Nakato, 1998	Nakato, 1981a
679.1	8	Ungaged Tributary Area		1,160										
679.1	8	L&D No. 8		64,770						806,333				
671	9	Upper Iowa nr. Dorchester, IA	05388250	770	351,318	0.90	39,035	0.10	390,353		6	1976-1981	Nakato, 1998	Nakato, 1981a
647.9	9	Ungaged Tributary Area		1,070										
647.9	9	L&D No. 9		66,610						390,353				
634.8	10	Ungaged Tributary Area		890										
634.8	10	Mississippi River at McGregor, IA	05389500	67,500	1,884,600	0.90	209,400	0.10	2,094,000	0	20	1976-1995	Nakato, 1998	Nakato, 1981a
630.7	10	Wisconsin River at Muscoda, WI	05407000	10,400	284,580	0.51	273,420	0.49	558,000		10	1974-1983	Rose, 1992	Rose, 1992
615.1	10	Ungaged Tributary Area		1,700										
615.1	10	L&D No. 10		79,600						558,000				
608.1	11	Turkey River at Garber, IA	05412500	1,545	1,152,449	0.71	463,436	0.29	1,615,885		16	1958-1996	Nakato, 1998	Hsu, 1982
593	11	Grant River at Burton, WI	05413500	267	68,500	0.90	7,611	0.10	76,111		18	1977-1995	Nakato, 1998	Nakato, 1981a
588.5	11	Platte River nr Rockville, WI	05414000	142	56,300	0.90	6,256	0.10	62,556			Estimated	Hsu, 1982	Nakato, 1981a
586.4	11	Little Maquoketa R. at Durango, IA	05414500	130	65,600	0.90	7,289	0.10	72,889			Estimated	Hsu, 1982	Nakato, 1981a

River Mile	Pool	Station/Tributary/Location	Gage No.	Drainage Area (sq. mi.)	Annual Suspended Load (Q_s) Discharge (tons/year)	Q_s/Q_t Ratio	Annual Bed Load (Q_b) Discharge (tons/year)	Q_b/Q_t Ratio*	Annual Total Load (Q_t) Discharge (tons/year)	Total Tributary Q_t to Pool (tons/year)	Record Length (years)	Q_s Record Period	Q_s Estimate Source	Q_b/Q_t Estimate Source
583	11	Ungaged Tributary Area		416										
583	11	L&D No. 11		82,100						1,827,440				
579.3	12	Mississippi R. at East Dubuque, IL		82,100	4,739,700	0.90	526,633	0.10	5,266,333		29	1968-1996	Nakato, 1998	Nakato, 1981a
564.8	12	Galena River at Buncombe, WI	05415000	125	37,600	0.90	4,178	0.10	41,778			Estimated	Hsu, 1982	Nakato, 1981a
556.7	12	Ungaged Tributary Area		275										
556.7	12	L&D No. 12		82,500						41,778				
548.6	13	Maquoketa R. near Maquoketa, IA	05418500	1,553	971,442	0.95	48,123	0.05	1,019,565		16	1979-1997	Nakato, 1998	Hsu, 1982
545.1	13	Apple River nr Hanover, IL	05419000	247	157,000	0.90	17,444	0.10	174,444			Estimated	Hsu, 1982	Nakato, 1981a
536.5	13	Plum River below Carrol Creek, IL	05420000	230	149,000	0.90	16,556	0.10	165,556			Estimated	Hsu, 1982	Nakato, 1981a
522.5	13	Ungaged Tributary Area		1,070										
522.5	13	L&D No. 13		85,600						1,359,565				
506.5	14	Wapsipinicon R. near DeWitt, IA	05422000	2,330	645,475	0.93	51,056	0.07	696,531		27	1968-1996	Nakato, 1998	Hsu, 1982
493.3	14	Ungaged Tributary Area		470										
493.3	14	L&D No. 14		88,400						696,531				
482.9	15	Ungaged Tributary Area		100										
482.9	15	L&D No. 15		88,500						0				
479	16	Rock River nr. Joslin, IL	05446500	9,549	1,360,000	0.96	55,782	0.04	1,415,782			1978-1980	Hsu, 1982	Hsu, 1982
479	16	Green River nr Geneseo, IL	05447500	1,003	271,745	0.90	30,194	0.10	301,939		13	1983-1996	Nakato, 1998	Nakato, 1981a
457.2	16	Ungaged Tributary Area		448										
457.2	16	L&D No. 16		99,500						1,717,721				
437.1	17	Ungaged Tributary Area		100										
437.1	17	L&D No. 17		99,600						0				
434	18	Iowa River at Wapello, IA	05465500	12,500	2,828,202	0.92	237,267	0.08	3,065,469		19	1979-1997	Nakato, 1998	Hsu, 1982
431.3	18	Edwards River nr New Boston, IL	05466500	445	261,000	0.90	29,000	0.10	290,000			1979-1980	Hsu, 1982	Nakato, 1981a
427.5	18	Pope Creek nr Keithsburg, IL	05467000	183	119,000	0.90	13,222	0.10	132,222			Estimated	Hsu, 1982	Nakato, 1981a
410.5	18	Ungaged Tributary Area		872										
410.5	18	L&D No. 18		113,600						3,487,692				
409.9	19	Henderson Creek nr Oquawka, IL	05469000	432	321,000	0.90	35,667	0.10	356,667			1978-1980	Hsu, 1982	Nakato, 1981a
404.1	19	Ungaged Tributary Area		0										
404.1	19	Mississippi River at Burlington, IA	05469720	114,032	10,230,900	0.90	1,136,767	0.10	11,367,667	356,667	29	1968-1996	Nakato, 1998	Nakato, 1981a
396	19	Skunk River at Augusta, IA	05474000	4,303	2,774,483	0.99	33,698	0.01	2,808,181		22	1976-1997	Nakato, 1998	Hsu, 1982
364.2	19	Ungaged Tributary Area		665										
364.2	19	L&D No. 19		119,000						2,808,181				
363.9	20	Mississippi River at Keokuk, IA	05474500	119,000	12,500,000	0.90	1,388,889	0.10	13,888,889		29	1968-1996	Nakato, 1998	Nakato, 1981a
361.4	20	Des Moines R. at St. Francisville, MO	05490600	14,330	6,531,800	0.90	725,756	0.10	7,257,556		18	1978-1995	Nakato, 1998	Nakato, 1981a
353.6	20	Fox River at Wayland, MO	05495000	400	298,000	0.90	33,111	0.10	331,111			Estimated	Hsu, 1982	Nakato, 1981a
343.2	20	Ungaged Tributary Area		570										
343.2	20	L&D No. 20		134,300						7,588,667				
341	21	Bear Creek nr Marcelline, IL	05495500	349	239,000	0.90	26,556	0.10	265,556			Estimated	Hsu, 1982	Nakato, 1981a
337.3	21	Wyaconda River above Canton, MO	05496000	393	352,000	0.90	39,111	0.10	391,111			Estimated	Hsu, 1982	Nakato, 1981a
324.9	21	Ungaged Tributary Area		158										
324.9	21	L&D No. 21		135,200						656,667				
323	22	North Fabius R. at Monticello, MO	05497000	452	365,000	0.90	40,556	0.10	405,556			Estimated	Hsu, 1982	Nakato, 1981a
323	22	Middle Fabius R. nr Monticello, MO	05498000	393	317,000	0.90	35,222	0.10	352,222			Estimated	Hsu, 1982	Nakato, 1981a

River Mile	Pool	Station/Tributary/Location	Gage No.	Drainage Area (sq. mi.)	Annual Suspended Load (Q_s) Discharge (tons/year)	Q_s/Q_t Ratio	Annual Bed Load (Q_b) Discharge (tons/year)	Q_b/Q_t Ratio*	Annual Total Load (Q_t) Discharge (tons/year)	Total Tributary Q_t to Pool (tons/year)	Record Length (years)	Q_s Record Period	Q_s Estimate Source	Q_b/Q_t Estimate Source
323	22	South Fabius R. Nr Taylor, MO	05500000	620	550,000	0.90	61,111	0.10	611,111			Estimated	Hsu, 1982	Nakato, 1981a
321	22	North River at Palmyra, MO	05501000	373	364,000	0.90	40,444	0.10	404,444			Estimated	Hsu, 1982	Nakato, 1981a
301.2	22	Ungaged Tributary Area		462										
301.2	22	L&D No. 22		137,500						1,773,333				
301.2	22	Mississippi River at Hannibal, MO		137,500	22,625,400	0.90	2,513,933	0.10	25,139,333		12	1967-1978	Nakato, 1998	Nakato, 1981a
284.1	24	Salt River nr. New London, MO	05508000	2,480	827,400	0.90	91,933	0.10	919,333		9	1981-1989	Nakato, 1998	Nakato, 1981a
273.4	24	Ungaged Tributary Area		920										
273.4	24	L&D No. 24		140,900						919,333				
241.5	25	Ungaged Tributary Area		1,100										
241.5	25	L&D No. 25		142,000						0				
217.5	26	Illinois River at Valley City, IL	05586100	26,744	6,310,400	0.90	701,156	0.10	7,011,556		17	1980-1996	Nakato, 1998	Nakato, 1981a
217.5	26	Mississippi River below Grafton, IL	05587455	171,300	29,377,500	0.90	3,264,167	0.10	32,641,667		4	1991-1994	Nakato, 1998	Nakato, 1981a
202.9	26	Ungaged Tributary Area		200										
202.9	26	L&D No. 26		171,500						7,011,556				
202.9	OR	Mississippi River at Alton, IL	05587500	171,500	29,940,500	0.90	3,326,722	0.10	33,267,222		15	1990-1992	Nakato, 1998	Nakato, 1981a
195	OR	Missouri River		525,500	101,627,300	0.90	11,291,922	0.10	112,919,222			Estimated		
180	OR	Ungaged Tributary Area		0										
180	OR	Mississippi River at St. Louis, MO	07010000	697,000	131,567,800	0.90	14,618,644	0.10	146,186,444	112,919,222	45	1948-1994	Nakato, 1998	Nakato, 1981a
161	OR	Meramec River nr. Eureka, MO	07019000	3,788	1,478,900	0.90	164,322	0.10	1,643,222		7	1980-1986	Nakato, 1998	Nakato, 1981a
117.6	OR	Kaskaskia River nr. Venedy, IL	05594100	4,393	581,600	0.90	64,622	0.10	646,222		17	1980-1996	Nakato, 1998	Nakato, 1981a
109.9	OR	Ungaged Tributary Area		3,419										
109.9	OR	Mississippi River at Chester, IL	07020500	708,600	162,793,400	0.90	18,088,156	0.10	180,881,556	2,289,444	4	1981-1984	Nakato, 1998	Nakato, 1981a
75.6	OR	Big Muddy R. at Murphysboro, IL	05599500	2,169	242,000	0.90	26,889	0.10	268,889		16	1981-1996	Nakato, 1998	Nakato, 1981a
43.7	OR	Ungaged Tributary Area		2,431										
43.7	OR	Mississippi R. at Thebes, IL	07022000	713,200	115,632,983	0.90	12,848,109	0.10	128,481,092	268,889	13	1981-1994	Nakato, 1998	Nakato, 1981a
0	OR	Ohio River												

*If Q_b/Q_t = 0.10 and Nakato (1981a) is cited as reference then the bed load is an estimate based on Nakato (1981a).

Monthly suspended sediment-load discharge estimates were developed from daily suspended sediment discharge measurements. In estimating monthly suspended-load discharge, a general rule was applied such that if more than half of the daily data were missing for a particular month, the monthly total for that month was set to zero. If less than half of the daily data were missing for a particular month, a monthly total was estimated by calculating the mean daily value for the measured number of days and multiplying it by the number of days for that month. Estimated monthly totals were then tabulated for each station for different years. Yearly totals were obtained by adding monthly totals. If monthly totals were missing for some months of a year, a monthly average was determined and then multiplied by twelve to obtain the yearly total. If monthly totals were missing for more than six months for a particular year, that year was excluded from the yearly average. The annual suspended-load discharge was obtained by dividing the yearly sum by the number of recorded years.

Also included on Table 5-3 are average annual suspended sediment load estimates for tributaries developed as part of prior studies. Estimates developed by others (Rose, 1992; Hsu, 1981) were adopted in cases when superior sediment measurement records could not be identified. The specific source of each suspended sediment load estimate is provided in the table. As seen in the table, nine tributaries were found to deliver more than one million tons/year of suspended sediment load to the UMR. These major suspended sediment sources include the Minnesota River ($1.3x10^6$ tons/yr), the Turkey River ($1.2x10^6$ tons/yr), the Rock River ($1.4x10^6$ tons/yr), the Iowa River ($2.8x10^6$ tons/yr), the Skunk River ($2.8x10^6$ tons/yr), the Des Moines River ($6.5x10^6$ tons/yr), the Illinois River ($6.3x10^6$ tons/yr), Missouri River ($101.6x10^6$ tons/yr) and the Meramec River ($1.5x10^6$ tons/yr).

As can be seen in Table 5-3, the suspended-load discharge along the UMR increases in the downstream direction, ranging from $9x10^5$ tons/yr at Winona, MN (RM 725.7) to $163x10^6$ tons/yr at Chester, IL (RM 109.9), an increase of approximately 180 times. A sudden increase in the suspended-load discharge at St. Louis, MO is attributable to heavy sediment input from the Missouri River. The Missouri River actually carries more sediment load than the UMR upstream of their confluence. The annual suspended-load discharge at St Louis is more than four times larger than that at Alton, IL (RM 202.9) and for the whole reach, between Anoka, Minnesota, and Thebes, Illinois, the load increases by about factor of 618.

Plots of the annual suspended sediment load estimates developed for UMR mainstem and tributary sediment measurement stations are located in Appendix D. An example of the plots for several tributary stations is shown in Figure 5-14. As seen in the figure, the estimated annual suspended-load discharges for the UMR tributaries display significant temporal variations. It is evident from the plots that short measurement records may result in erroneous estimates of average suspended sediment load. Furthermore, if possible, analyses using sediment transport estimates should consider similar periods of record.

Bed Load Transport Estimates

Estimates of bed load transport along the UMR and its tributaries were obtained either from previous studies or developed by assuming that the ratio of bed load sediment discharge (Qs_b) to total load sediment discharge (Qs_t) is equal to 10 percent. Since the total sediment load is equal to the sum of the suspended load sediment discharge and the bed load sediment discharge, this is equivalent to assuming that the ratio of suspended sediment load to total sediment load is equal to 90 percent. This assumption has been verified by bed load measurements made along various tributaries to the UMR (Nakato, 1981; Hsu, 1982). Estimates of bed load transport defined by Rose (1992) were used for the Chippewa River, Black River, and Wisconsin River. A summary of the total load and bed load sediment transport estimates for the UMR, are presented in Table 5-3. Plots of total load, suspended load, and bed load sediment supply to UMR navigation pools are presented in Figure 5-12 and Figure 5-13.

5.3.2.2 Illinois Waterway

The most detailed sediment transport estimates for the IWW basin were previously developed as part of a sediment budget analysis (Demissie et al., 1992). Available suspended sediment discharge measurement records were used to develop sediment yield estimates for all major tributaries in the basin. The tributary sediment yield information was compared with sediment transport measured along the IWW at Valley City to determine the amount of sediment deposited within the IWW valley. On average, 13.8 million tons of sediment were determined to be delivered to the IWW valley from tributary streams each year. The IWW was determined to discharge 5.6 million tons of sediment per year for the time period analyzed (1981-1990). A total of about 8.2 million tons of the sediment delivered by tributary streams was determined to be deposited within the IWW valley each year. Major sediment contributors to the IWW, from upstream to downstream, include the Kankakee River which joins the Dresden Pool, the Vermilion River which is tributary to Peoria Pool, and the Mackinaw, Spoon, Sangamon, and La Moine Rivers which join the La Grange Pool.

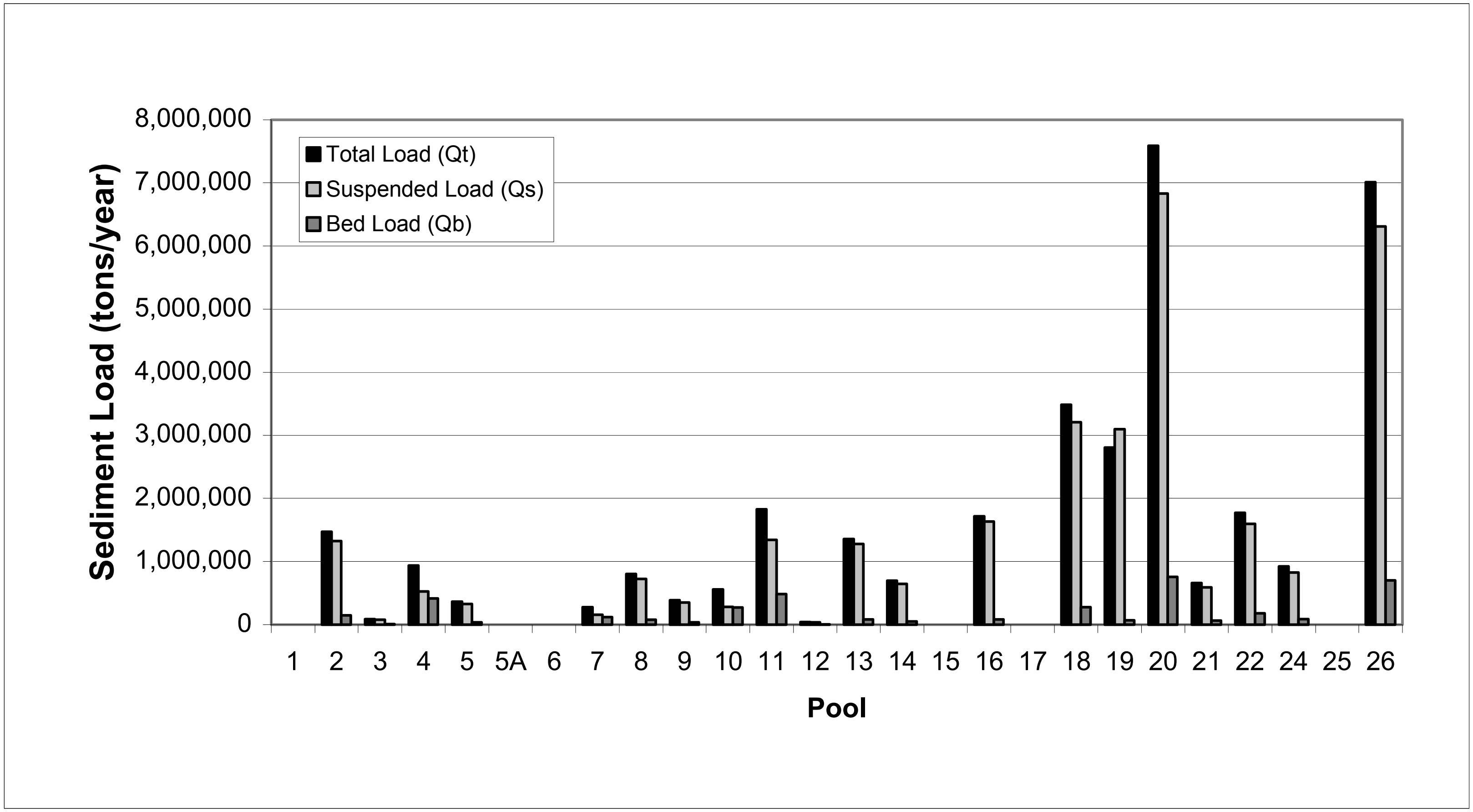


Figure 5-12: Average annual tributary sediment load delivered to each pool along the UMR (based on Table 5-3).

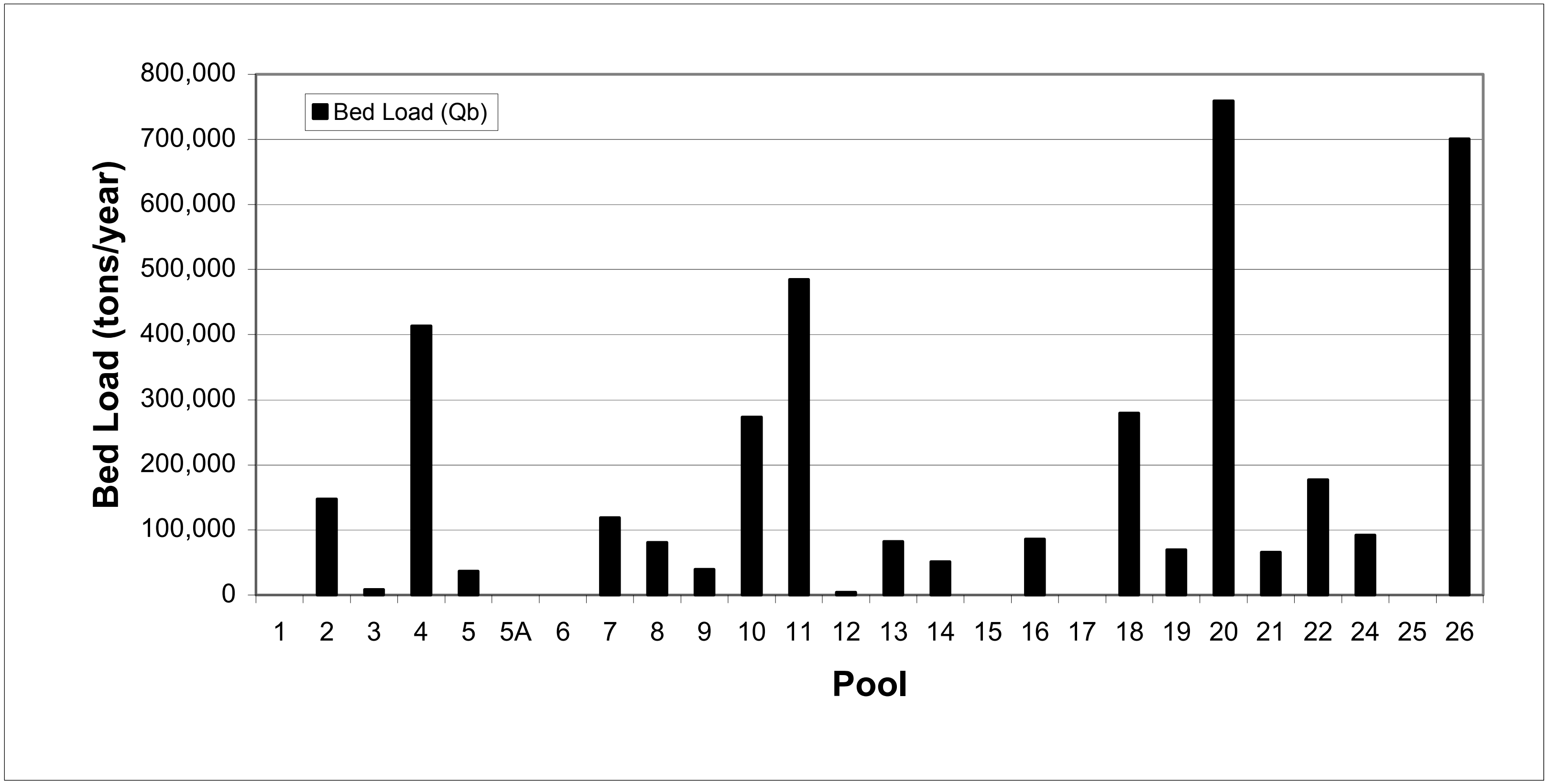


Figure 5-13: Average annual tributary bed load delivered to each pool along the UMR.

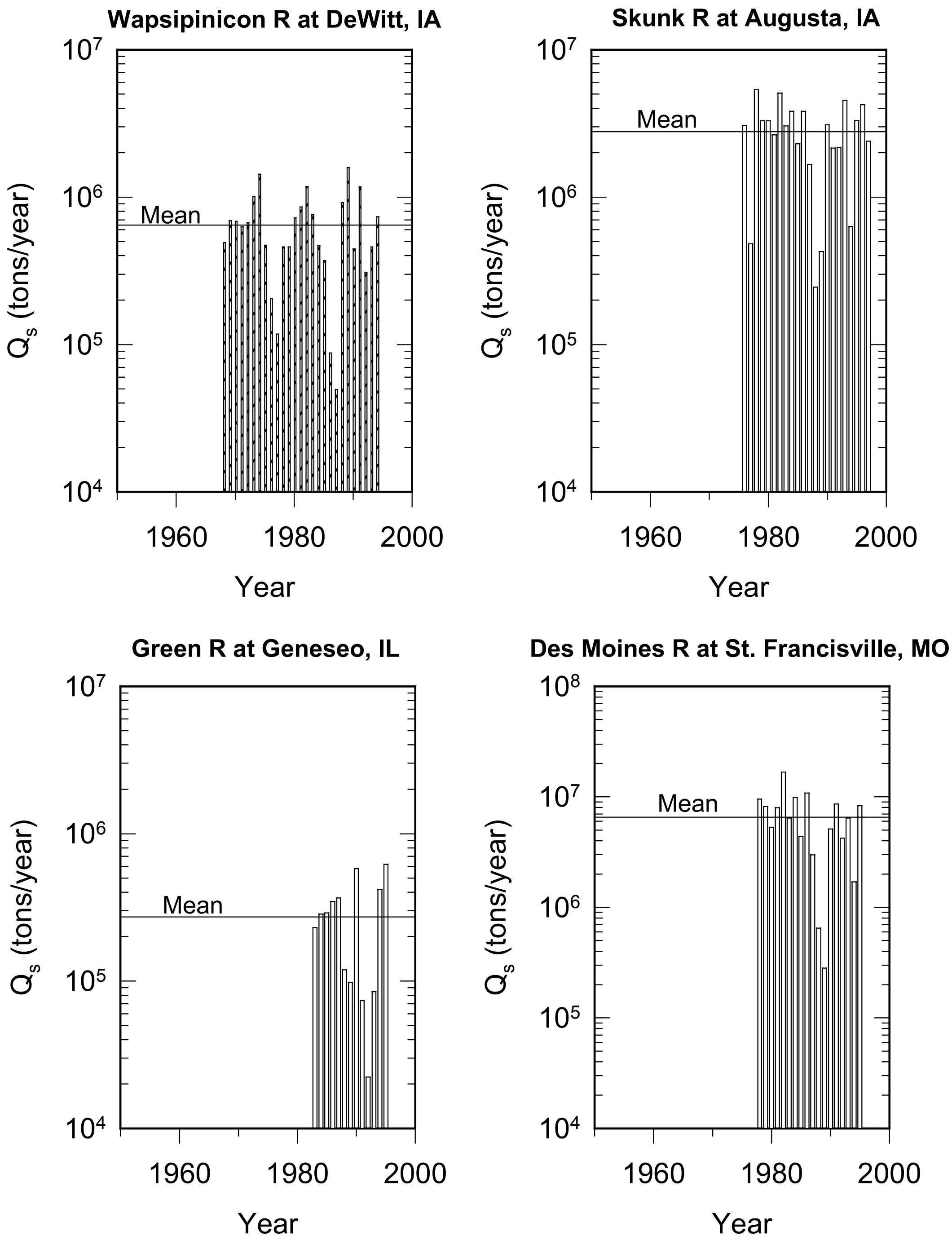


Figure 5-14: Example plots of estimated annual suspended sediment discharge for UMR tributaries. Plots for other mainstem and tributary suspended measurement stations are presented in Appendix D.

Table 5-4: Long term trends in suspended load along the UMR (source: USACE (1981))

		Average Annual Suspended-Sediment Load (tons)		
Station	**River Mile**	**Before 1953**	**1953-1967**	**After 1967**
Hannibal	309.2	36,254,760	22,430,309	24,510,652
St. Louis	179.1	319,934,918	105,155,087	114,102,196

5.3.3 Long Term Trends in Sediment Transport

The long-term suspended sediment records of four UMR mainstem sediment measurement stations are shown in Figure 5-15. Also shown on the figure are trend lines for each data set. The data for all four measurement stations indicate a decreasing trend in suspended sediment load along the UMR since the mid-1940s. The decreasing trend is most prominent for the measurement station at St. Louis, which is dominated by the suspended sediment supply from the Missouri River. Several large dams and reservoirs were constructed on the Missouri River during the period of record. Similar decreasing long-term trends for suspended sediment loads along the UMR were documented by the USACE (1981). Data for two suspended sediment measurement stations identified by the USACE (1981) are reproduced in Table 5-4. The decreasing trend for suspended sediment load along the UMR is consistent with other observations and conclusions of the current study. These include improved agricultural land use practices (Section 3.3), construction of numerous large reservoirs on tributaries (Section 5.4.6), and the slowing rates of sedimentation in backwater areas (Section 6.2.2).

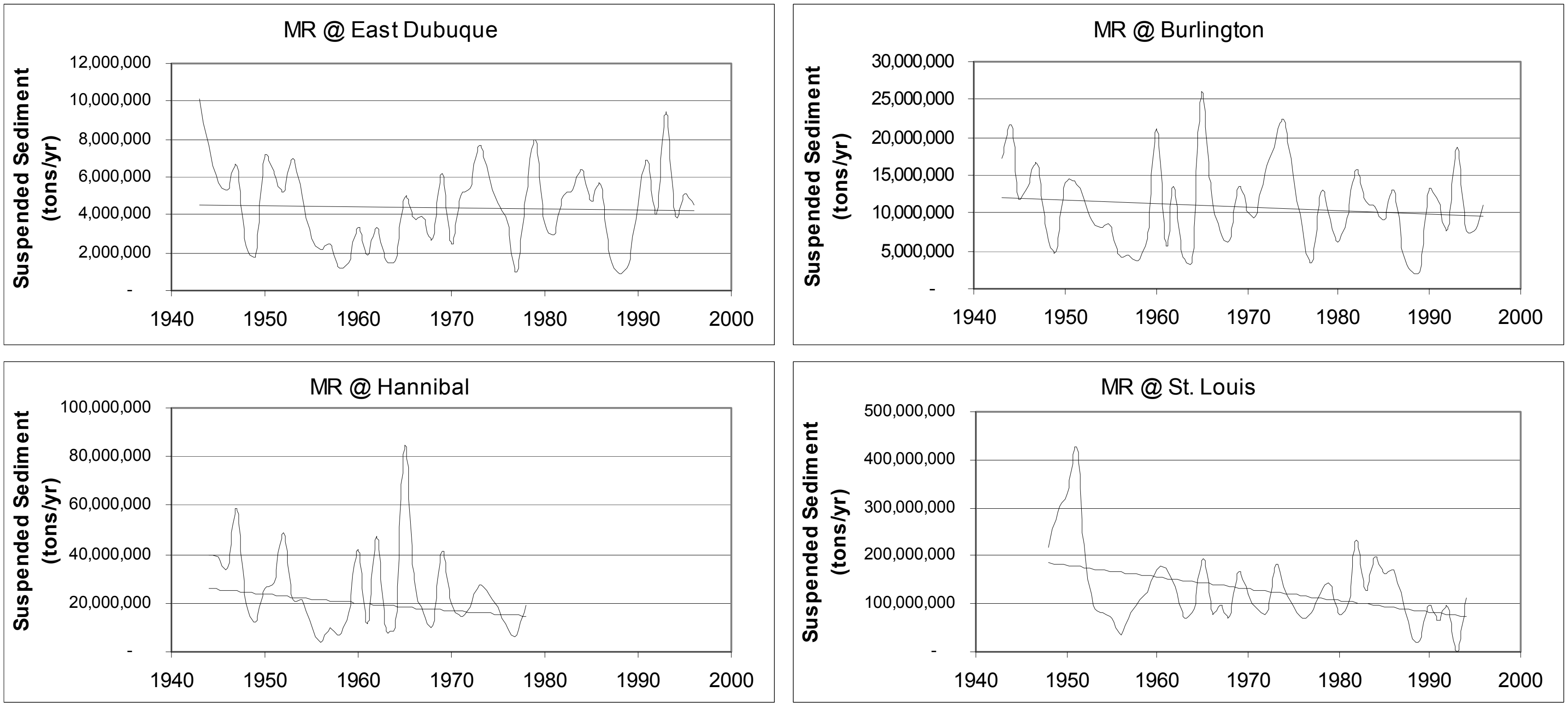


Figure 5-15: Suspended sediment transport along the mainstem of the Mississippi River (USACE (1981)).

5.4 HUMAN INFLUENCES

Significant human influences on the Upper Mississippi River system have been occurring for over 150 years (EMTC, 1998). Human activities have altered the river environment in many ways. This section discusses several human actions that have affected the physical and ecological conditions of the UMR and IWW.

5.4.1 Navigation Channel

Navigation along the UMR has been instrumental for human development of the Midwest. Development of the current navigation system occurred in various stages. The earliest improvements for navigation occurred as early as the 1830s. Congress authorized the existing 9-ft Channel Project in 1930. The 9-ft Channel Project provides safe navigation conditions throughout the approximate 850-mile distance between Cairo, Illinois and St. Paul, Minnesota along the UMR and between the confluence with Mississippi River and Lake Michigan along IWW, a distance of about 330 river miles. The locks and dams of the project provide slack water navigation conditions over topographic barriers, between St. Louis, Missouri and St. Paul, Minnesota. Generally, the UMR navigation channel is 300 feet wide in straight reaches of the river and 500 feet wide in bends. Although, the navigation channel typically represents only a portion of the main channel of the river, the water impoundments associated with locks and dams, and other hydraulic control structures, such as wing dams, that are required to operate the navigation channel, generally influence the entire river channel and its backwater areas.

The authorized project dimension of the existing channel along the IWW between Grafton and Lockport, Illinois is 300 feet, with additional widths at bends, except in the Marseilles Canal where it is 200 feet. The authorized project dimension of the Chicago Sanitary and Ship Canal is 160 feet, and the authorized project dimension of the Calumet-Sag Channel is 225 feet.

5.4.2 Wing Dams

Large numbers of hydraulic control structures, referred to as wing dams, have been constructed along the UMR. Very few wing dams have been constructed along the IWW. The wing dams are intended to control the magnitude, velocity, and direction of flow along the river. By controlling the hydraulics of flow, wing dams also influence the location of channel erosion and sedimentation. Sediments accumulate in the flow separation zones created by the wing dams. Sediments dredged from the main channel are often placed along the channel bank between wing dams. Present policy of the St. Paul District is not placing dredge material between wing dams.

The construction of wing dams along the UMR began as early as the late 1800s. Literally, hundreds of wing dams have since been constructed along the route of the 9-ft Navigation Channel. In the early days, wing dams were constructed of consecutive layers of rock and willow bundles joined to form large mats and/or a line of posts driven vertically into the substrate perpendicular to the main flow. Generally, the wing dams concentrate flow in the navigation channel, induce sediment deposition within border areas of the channel, and control flow into and along secondary channels. Many wing dams have been buried within sediment deposits and are no longer discernable in recent aerial photography. However, construction of the locks and dams reduced the need for many of the structures, and they were never replaced. In the lower pooled reaches and especially in the Mississippi River below the confluence with the Missouri River, wing dams are common and are visible above the water line except during floods.

The locations of wing dams constructed in various time periods are plotted on maps contained in Appendix C. The pooled reach of the UMR has the most complete data on the wing dams. In Pool 4, almost all of the wing dams are located downstream of Lake Pepin. In Figure 5-16 the number of wing dams per river mile is plotted for the UMR. The mean number of wing dams per river mile for the pooled reach and the Open River are noted in the figure as dashed lines. For comparison purposes, the Open River was divided into eight 25-mile long reaches.

Generally, the number of wing dams per river mile is negatively correlated to the thalweg slope of the river (the thalweg slope of the UMR geomorphic reaches is plotted in Figure 5-57), the steeper the slope of the river, the few number of wing dams. The exception to this rule is found in Pools 5 through 9 which has 8.45 wing dams per river mile (wd/rm). Construction of more wing dams per river mile was likely required in this geomorphic reach due to its island-braided channel form prior to construction of the 9-ft Channel Project (See Section 5.2). For Pools 10 through 13, the number of wing dams employed is higher than average (4.39 wd/rm) as the slope is relatively flat. For Pools 14 through 17, the number of wing dams employed is relatively low as the geomorphic reach is relatively steep (3.32 wd/rm) and bedrock controls the location of the pools. Due to the height of the dam and its significant impoundment, Pool 19 has the lowest number of wing dams per river mile. The number of wing dams used per mile for Pools 20-26 is 3.12 wd/rm. For the Open River reach, the average number of wing dams employed increases 17 percent, to 4.01 wing dams per river mile. As is seen in the maps in Appendix C, most of the wing dams for the pooled reach were constructed before the construction of the locks and dams.

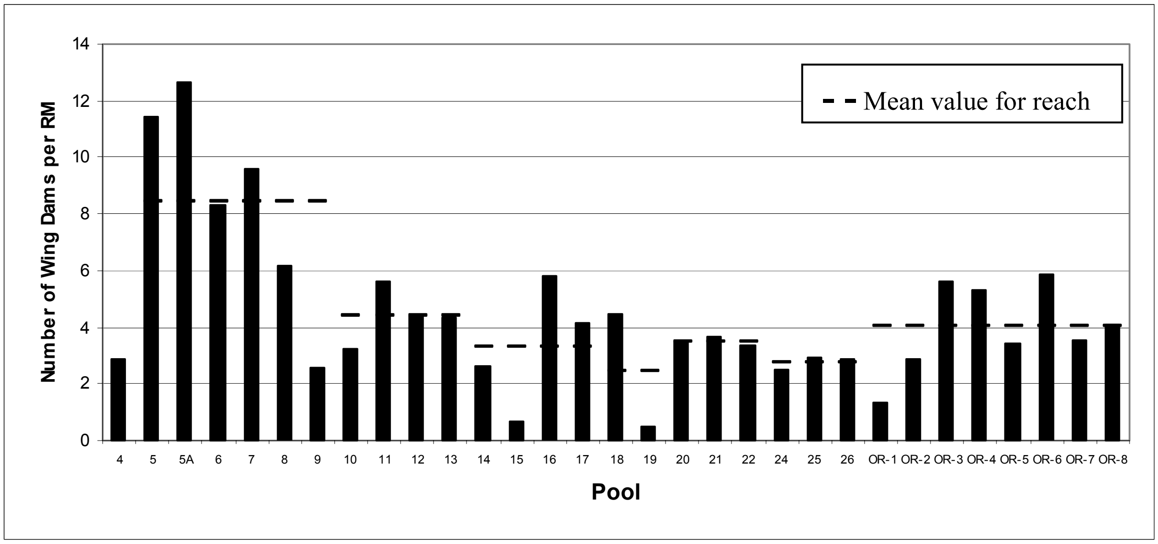


Figure 5-16: Number of wing dams per river mile along the UMR. The dashed lines represent mean number of wing dams for each geomorphic reach.

5.4.3 Locks and Dams

The majority of locks and dams along the UMR were constructed in the 1930s as a part of the 9-ft Channel Project. Exceptions include Lock and Dam 19 that began operation in 1913 and Lock and Dam 26, which was replaced in 1989. The location and size of the locks and dams was largely determined by the natural gradient of the river, the location of geologic controls which present obstacles to navigation, and confluences with major tributaries. A summary of the locations and characteristics of locks and dams along the UMR is presented in Table 5-5. A summary of the locks and dams along the IWW is presented in Table 5-6.

The length of each pool along the UMR and IWW is plotted in Figure 5-17 and Figure 5-18, respectively. The average length of a pool along the UMR is about 25 miles. The length of pools along the IWW vary significantly from upstream to downstream. Upstream of Starved Rock Lock and Dam the pools are relatively short and the lift between pools is large. Downstream, the Alton, La Grange, and Peoria Pools are extremely long and the lift between them is small. The length of the pools is correlated to the gradient of the river. The shortest pools are located within the steepest gradient reaches. The longest pools are Pool 19 along the UMR (46.3 miles) and Alton Pool along the IWW (80.2 miles). The flat pool elevation for each pool of both the UMR and IWW is plotted in Figure 5-19. It clearly shows that the slope of the lower portion of the IWW is considerably less than the slope of the UMR.

Table 5-5: Summary of locks, dams, and pools along the Upper Mississippi River.

Lock Name or Number	River Mile	Pool Length (mi)	Drainage Area (sq mi)	Average Lift (ft)	Width (ft)	Length (ft)	Percent of Time as Open River[2]	Began Operation
Lower St. Anthony Falls	854.1	0.6	19,680	25	56	400	N/A	1958
1	847.7	6.4	19,684	38	56	400	N/A	Original 7/3/17 Rebuilt 1938
2	815.2	32.5	36,990	12	110	600	1	1931
3	796.9	18.3	45,170	8	110	600	14	1938
4	752.8	44.1	57,100	7	110	600	4	1935
5	738.1	14.7	58,845	9	110	600	1	1935
5A	728.3	9.8	59,105	5	110	600	13	1936
6	714.2	14.1	60,030	6	110	600	7	1936
7	702.5	11.7	62,340	8	110	600	5	1937
8	679.1	23.4	64,770	11	110	600	4	1937
9	647.9	31.2	66,610	9	110	600	15	1937
10	615.1	32.8	79,600	8	110	600	18	1937
11	583.0	32.1	82,100	11	110	600	3	1937
12	556.7	26.3	82,500	9	110	600	4	1938
13	522.5	34.2	85,600	11	110	600	4	1938
14	493.3	29.2	88,400	11	110	600	<1	1939
15	482.9	10.4	88,500	16	110	600	1	1934
16	457.2	25.7	99,500	9	110	600	12	1937
17	437.1	20.1	99,600	8	110	600	22	1939
18	410.5	26.6	113,600	10	110	600	7	1938
19	364.2	46.3	119,000	38	110	1200	0	1913
20	343.2	21.0	134,300	11	110	600	21	1936
21	324.9	18.3	135,200	11	110	600	15	1938
22	301.2	23.7	137,500	11	110	600	12	1938
24	273.4	27.8	140,900	15	110	600	N/A	1936
25	241.4	32.0	142,000	15	110	600	N/A	1939
26 Melvin Price	202.9	38.5	171,500	24	110	1200	N/A	1938 original 1989[1] replacement
27	185.1	N/A	N/A	21	110	1200	N/A	1953

[1]Lock and Dam No. 26 was replaced at a location approximately 2 miles downstream from the original Lock and Dam site.
[2]From USGS Open-File Report 95-708

Table 5-6: Summary of locks, dams and pools along the Illinois Waterway.

Lock Name or Number	River Mile	Pool Length (mi)	Drainage Area (sq mi)	Average Lift (ft)	Width (ft)	Length (ft)	Percent of Time as Open River*	Began Operation
Lake Michigan	333.0	-	-	-	-	-	-	-
O'Brien	326.0	7.0	-	5	110	600	N/A	1968
Lockport	291.0	35.0	740	40	110	600	N/A	1933
Brandon	286.0	5.0	1,506	34	110	600	N/A	1933
Dresden	271.5	14.5	7,278	20	110	600	N/A	1933
Marseilles	244.6	26.9	8,259	24	110	600	N/A	1933
Starved Rock	231.0	13.6	11,056	17	110	600	N/A	1933
Peoria	157.7	73.3	14,554	6	110	600	42	1939
La Grange	80.2	77.5	25,648	5	110	600	48	1939
Alton	-	80.2		-	-	-	-	-

*Upper Locks and Dams do not go out of operation.

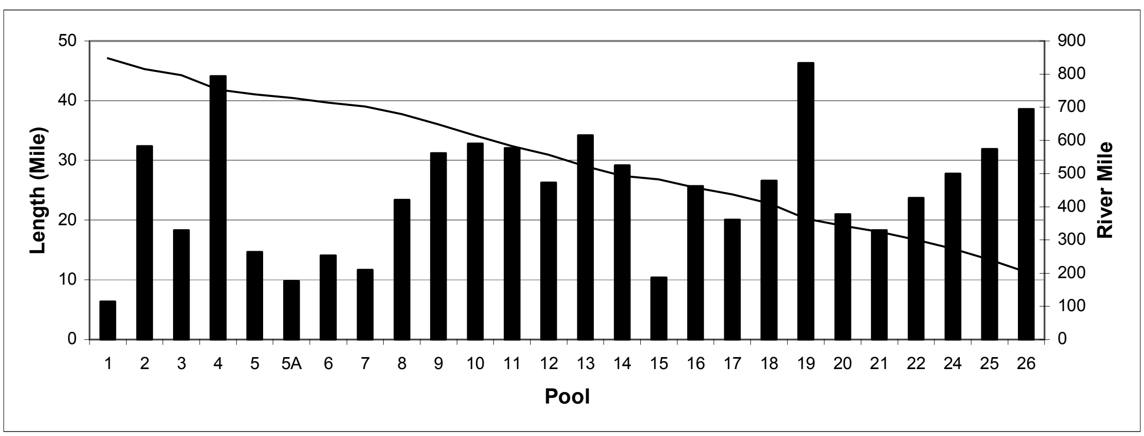


Figure 5-17: Length of pools for UMR and accumulated distance measured by river miles. The river mile of each pool is shown by the solid line.

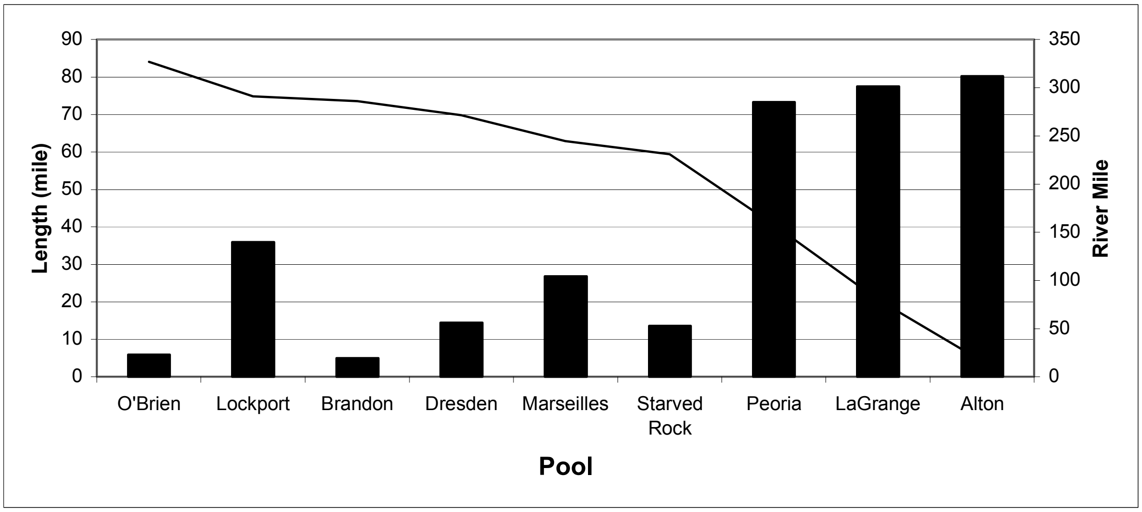


Figure 5-18: Length of pools for IWW and accumulated distance measured by river miles. The river mile of each pool is shown by the solid line.

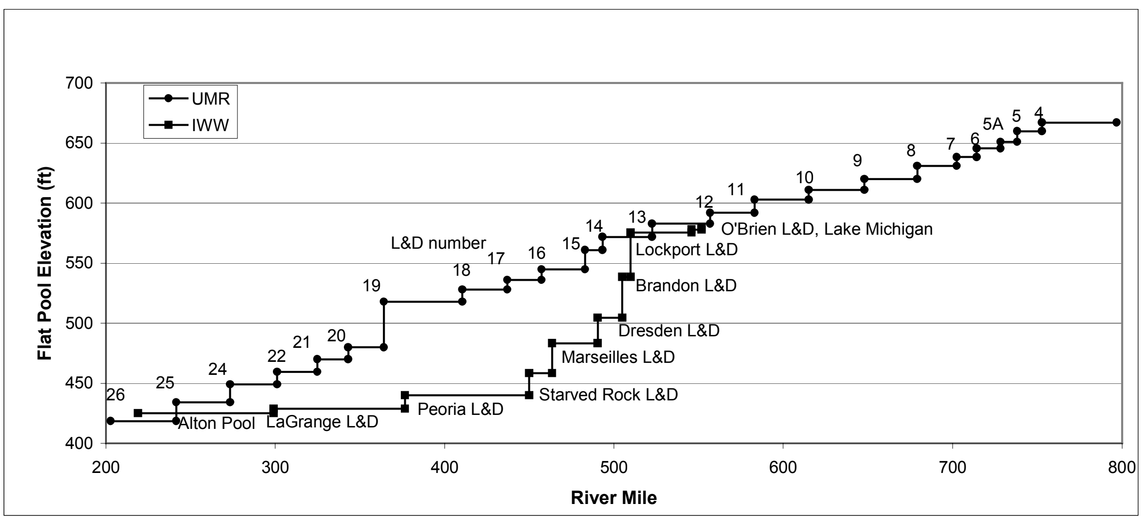


Figure 5-19: Flat Pool Elevation for UMR and IWW pools plotted against river mile.

5.4.4 Dredging

In the following sections, historic dredging activities along the UMR and IWW are examined. The locations of dredging and dredge material disposal sites along the waterways are evaluated through time. The relationship between tributary sediment supply and dredging is also explored. Additional analysis of dredging and material placement related to ecological issues along the UMR and IWW is presented in Volume 2.

5.4.4.1 Upper Mississippi River

Dredging of sediment deposits is routinely conducted along the UMR and IWW as part of the operation and maintenance activities of the 9-ft Channel Project. The dredging is necessary to maintain adequate depths for safe navigation. Examination of historic records of dredging provides an understanding of the location, amount, timing, and disposal practices associated with dredging activities. General trends may be identified from the historic information that are useful to describe the response of the river system to human activities and project future conditions.

The historic average annual amount of dredging within the UMR navigation pools is plotted for three time periods in Figure 5-20. The Corps tabulated the dredging data in cubic yards so density of 96.3 lb/ft^3 was used to express the dredge material in tons. In Figure 5-21 the same data, divided by the length of each associated pool, are plotted to illustrate the historic intensity of dredging among the pools. Available Geographical Information System (GIS) information was used to produce maps of the locations of dredging and associated dredged material placement sites by time period. Also shown on the maps are the locations of wing dams. An example of these maps is shown in Figure 5-24. Electronic files for the maps, which can be plotted at full size, are presented in Appendix C.

The available historic dredging data, Figure 5-20 and Figure 5-21, indicate that annual dredging has decreased over time in almost every pool along the UMR. The decrease in dredging is attributed to improved agricultural land use practices, construction of numerous large reservoirs on most major tributaries, and improved sediment management practices resulting from environmental laws, changing dredging philosophies and economic considerations. It is also recognized that remobilization of stored sediments is a factor in the supply of coarse sediment to the UMR. The remobilization of stored material may delay the impacts of other influences, such as improved land use practices and reservoirs. The concentration of flow and general narrowing of the main channel caused by wing dams, deposition of sediment in channel borders and backwater areas, and dredging may have also increased the sediment transport capacity of the main channel.

By far, the largest dredging amounts along the UMR occurred in Pools 25 and 26 and the smallest amounts of dredging occur in the rock gorge through Pools 14 to 16. The amount of dredging in Pool 4 is noted to be significantly larger than most other pools and has not decreased in the last 35 years. The dredging in Pool 4 is associated with the large bed load contribution supply of the Chippewa River. A sediment trap was constructed at the mouth of Chippewa River in the mid 1980s to control the bed load input to the Mississippi River and reduce downstream emergency dredging requirements (Personal communication with J. Hendrickson, 1998).

Channel maintenance practices have improved in recent years. Reduced depth dredging, confined disposal of dredge material, and more efficient hydrographic surveying techniques have all contributed to reductions in annual dredge material volumes. For example, sediments dredged in the St. Paul District of the USACE, Pools 1 through 10 of the UMR, are now disposed of in locations outside of the active channel. This action prevents the sediments from reentering the river channel and eliminates the potential for reworking of the sediments (Personal communication with D. Wilcox, 1998).

Reduced depth dredging began in 1973 and resulted in an immediate reduction in dredging (Personal Communications with Hendrickson, 1998). Reduced depth dredging involved a reduction in the maximum dredging depth along the UMR from 13 or more feet to 11 to 13 feet in the St. Paul District and to 11 to 12 feet in Rock Island District (Personal communications with M. Cox, 1998). Reduced depth dredging is intended to maintains a smaller and slightly more efficient channel cross section in dredge cut areas, decreasing the trap efficiency of dredge cuts, and increasing the sediment load to the downstream reach. If the downstream reach can convey the inflowing sediment load while maintaining an adequate cross section for navigation, a net reduction in dredging has been achieved. However, it is noted that generally the total volume of required dredging would not change with reduced depth dredging, if the average sediment supply to the UMR remains the same. In fact, the frequency of dredging would be expected to increase if other conditions affecting sediment transport remained the same.

Figure 5-24 shows an example of the dredging location maps contained in Appendix C. These maps show, on a pool by pool basis, the location, shape, and size of dredge cuts, wing dams and dredged material placement sites. To allow analysis of dredging practices through time, the dredging data are plotted by decade for each pool. By analyzing the historic locations of dredge sites, dredged material placement sites, and wing dams, several conclusions can be made about dredging in Pools 11 through 26 along the UMR.

- For the first 10 to 20 years after the construction of locks and dams along the UMR, intense dredging occurred just downstream of the locks and dams. The intensity of dredging downstream of the locks and dams decreases faster with time than dredging in other location with the pools. This is probably due to a general narrowing and scour of the channel observed in the upstream portion of each pool (see Section 5.5) and subsequent deposition of that material. The main channel in this area has been narrowed and the flow concentrated by wing dams, placement of dredged material and sedimentation between wing dams, and overall slight main channel degradation. In Pool 18, wing dam work has moved chronic dredging over 7 miles downstream since rock work began in 1981 (Personal communications with Cox, 1998). The sediment transport capacity of the main channel has been effectively increased.

- The rapid decrease in dredging activity noted at the upstream end of most pools has caused the centroid of dredging activities within each pool to move downstream. The amount of dredging in the lower half of each pool has not noticeably increased.
- Generally, there is no concentration of dredging activity in the immediate vicinity of tributary confluences. However, several cases exist where the alluvial fan of a major tributary has concentrated dredging upstream of the mouth of the tributary. A good example of this condition is seen upstream of the mouth of Illinois River.
- In many instances, a dredging location is re-dredged decade after decade.
- Dredging locations are commonly associated with flow splits between the main channel and secondary channels.

5.4.4.2 Open River

For the Open River segment of the UMR, historic dredging data are only available since 1979. Mapping of this limited data set indicates that dredging activities are not concentrated in any single location of the Open River. It is noted that dredged materials are not removed from the active channel area of the UMR for disposal. Dredged materials are typically placed within the main channel for disposal (EMTC, 1998). Re-handling of previously dredged sediments at downstream locations is the probable impact of this sediment management policy.

5.4.4.3 Illinois Waterway

Historic dredging data for the IWW are limited to dredging amounts. No data are available for the Alton Pool. The available information indicates that dredging is generally concentrated in narrow reaches of the waterway. Available dredged material disposal sites are limited in most areas. Commonly, dredged materials are placed on narrow bank lines where the sediments can be easily remobilized from such locations (Personal communication with C. Beckert, 1998). It is likely that sediments are reworked by dredging several times as it moves along the river. USACE Rock Island District has recently developed and implemented two upland placement sites, near the mouth of Sangamon in 1996 and near the mouth of Mackinaw in 1998. The effects of these sites will be known over the next several years (Personal communications with Cox, 1998).

In Figure 5-22 the available historic dredging data for the IWW are plotted for each pool. The data are separated into three general time periods, 1950 to 1959, 1960 to 1979, and 1980 to 1996. Generally, the dredging amount decreased between the first and the second time period and then increase for the third time period for the LaGrange and Peoria Pools. For upstream pools, dredging data were only available for the last time period. In Figure 5-23, the dredging data was divided by pool length to illustrate dredging intensity among the pools. It is observed from the figure that dredging intensity increases going down the river with the largest dredging amounts per river mile in the LaGrange Pool. The LaGrange Pool is known to have the greatest tributary sediment supply (Demissie et al, 1992).

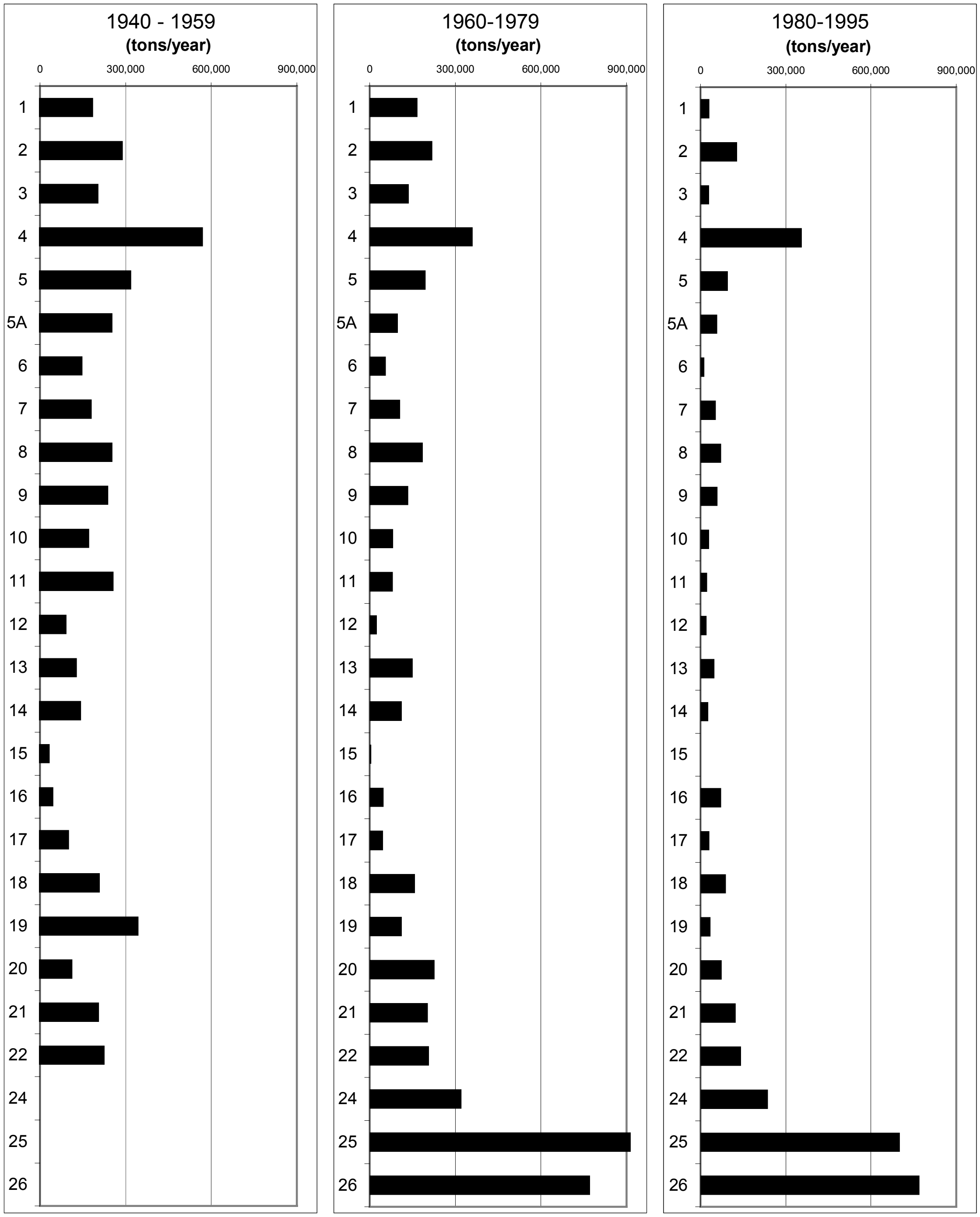


Figure 5-20: Average annual dredging for Upper Mississippi River in tons/year for Pools 1-26. Dredge data for Pools 24-26 is not available prior to 1967.

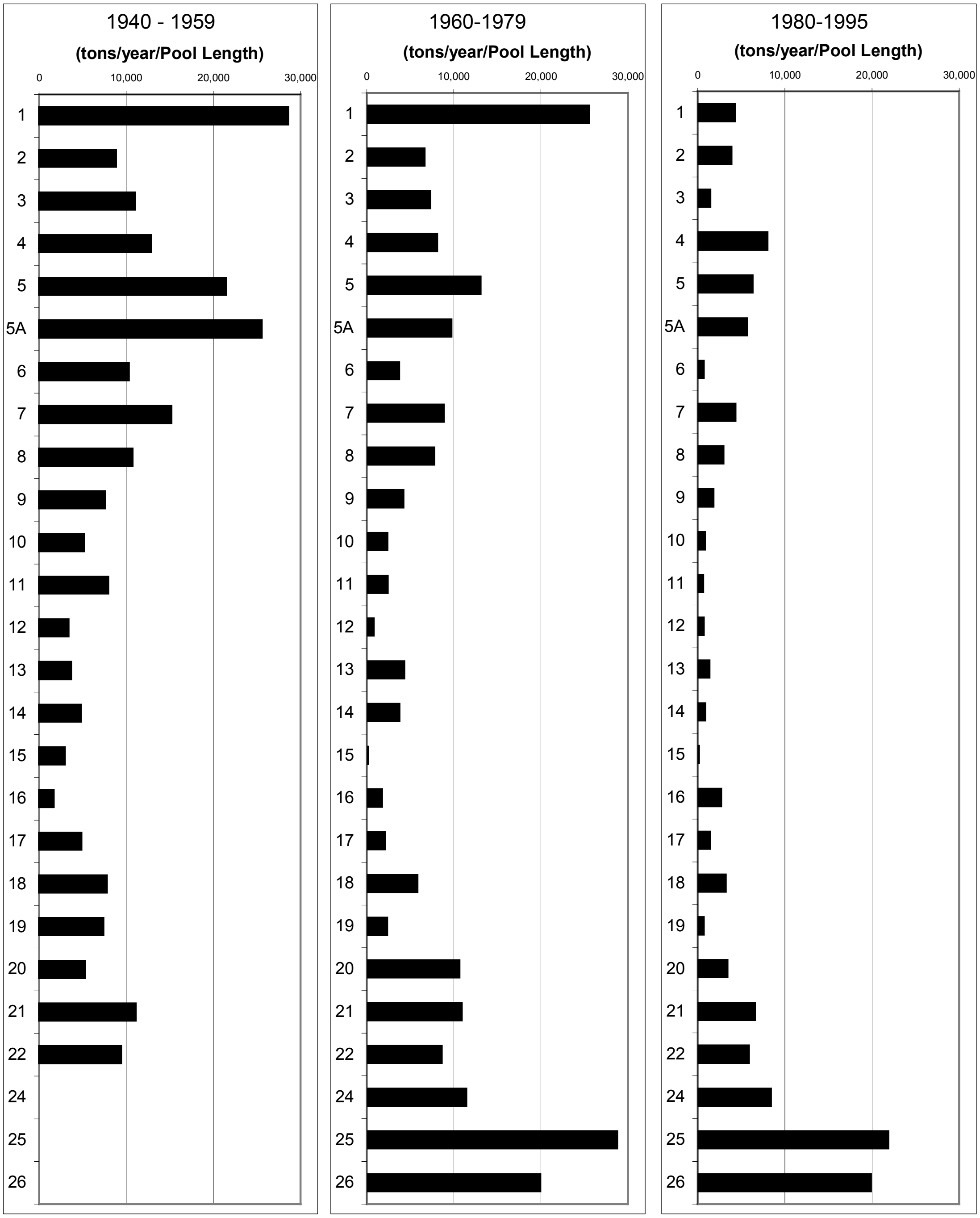


Figure 5-21: Average annual dredging for Upper Mississippi River in tons/year/(pool length) for Pools 1-26. Dredge data for Pools 24-26 is not available prior to 1967.

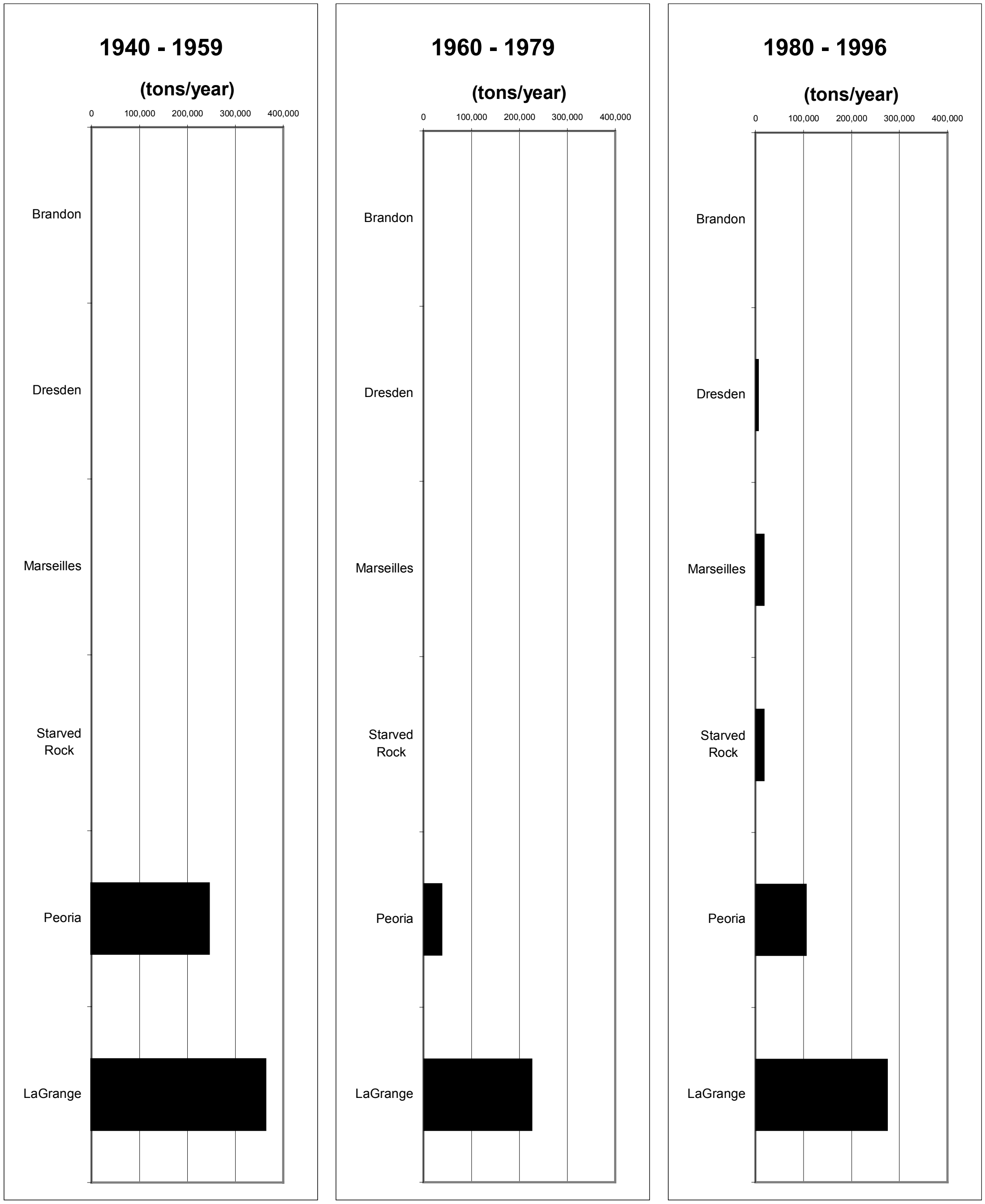


Figure 5-22: Average annual dredging for Illinois Waterway in tons/year. No dredge event was recorded upstream of Peoria before 1987.

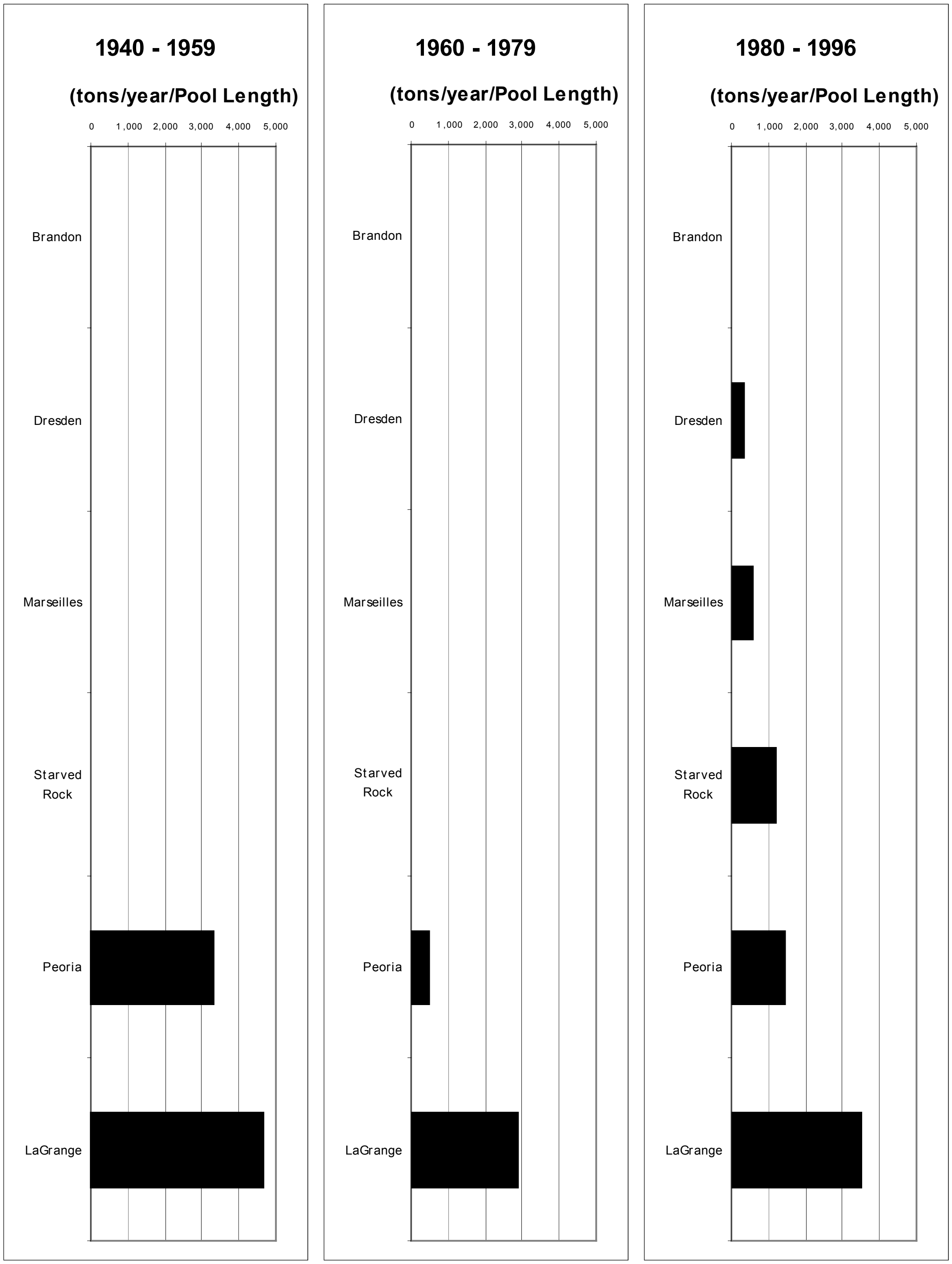


Figure 5-23: Average annual dredging for Illinois Waterway in tons/year/(pool length). No dredge event was recorded upstream of Peoria before 1987.

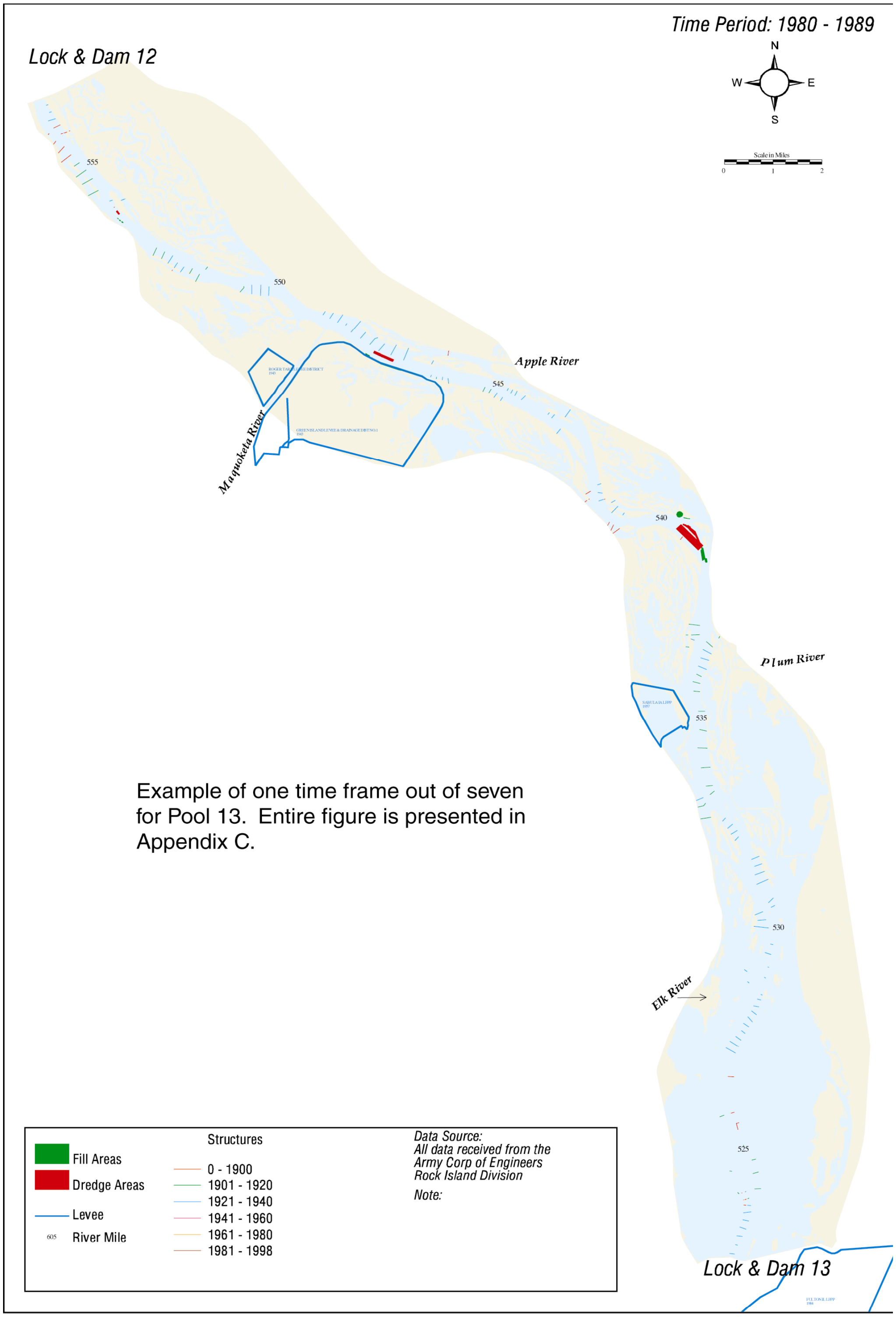


Figure 5-24: A schematic example of the dredging location maps. Each map shows the dredging location, placements sites and location of wing dams by decade for every pool and/or river reach. The electronic files for the maps for each pool are presented in Appendix C.

5.4.4.4 Bed Load Supply and Dredging

Since dredging activities generally involve the removal of bed load sediment deposits, a comparison was made of the estimated average annual bed load sediment supply from UMR tributaries to the average annual dredging amount within each UMR navigation pool. The comparison is shown in Figure 5-25. The bed load sediment supply estimates were developed as described in Section 5.3.

As seen from Figure 5-25, the average annual dredging amount is generally correlated with the bed load sediment supply. Major bed load sediment supplies, greater than 200,000 tons/year, join the UMR in the following pools:

- Pool 4 (Chippewa River)
- Pool 10 (Wisconsin River)
- Pool 11 (Turkey River)
- Pool 18 (Iowa River)
- Pool 20 (Des Moines River)
- Pool 26 (Illinois Waterway)

In Pool 4, dredging is approximately equal to 80 percent of the bed load supply from the Chippewa River. In several pools (Pools 10, 11, 18, and 20), the annual supply of bed load sediments greatly exceed the annual dredging amount. Conversely, the annual dredging amount greatly exceeds bed load supply in Pools 24 and 25. It is apparent from the figure that dredging is not the only sink for bed load sediment supply in each pool. Other sinks for bed load sediment supply that must be considered would include backwater areas, where dredging does not typically occur, and other downstream pools. The geomorphic reaches (see Section 5.2) reflect in some cases the approximate boundaries between sinks and sources along the river.

The imbalance between bed load sediment supply and dredging observed in Pools 10 and 11 is probably explained by deposition in the lower portion of Pool 11. In Section 5.6, analyses of historic cross sections for Pool 11 show an accumulation in the lower pool. The annual rate of sediment accumulation in Pool 11 for two historic time periods is also quantified in the sediment budget analysis presented in Chapter 6. As seen from that data, the annual sediment accumulation in Pool 11 from 1938 to 1951 (695,857 tons/year) is similar to the accumulation rate within the 1951 to 1995 time period (655,679 tons/year). Furthermore, the sediment accumulation rate for Pool 11 in the 1951 to 1995 time period is about 87 percent of the combined bed load supply to Pools 10 and 11 (758,011 tons/year). The sedimentation rate in the backwater areas for lower Pool 11 has decreased significantly as is discussed in Section 5.6 but the sedimentation in the main channel is still high. This has not yet led to increases in dredging, as the main channel is still relatively deep in the lower pool. However, it is reasonable to expect increased dredging requirements in the lower Pool 11 in future decades. It is also possible that sediment transport capacity of the main channel will increase as it narrows and becomes shallower. Ultimately, more of the bed load from the Wisconsin and Turkey Rivers may be passed on to Pools 12 and 13, which could lead to increased dredging in those pools.

Similarly, the imbalance between bed load sediment supply and dredging observed in Pool 18 is likely explained by deposition in Pool 19. Pool 19 has historically been a major sediment sink. As shown in the comparison of historic cross section data in Section 5.6, the amount of sediment deposited in recent years in the upstream portion of Pool 19 (294,678 tons/year) closely matches the estimated bed load sediment supply to Pool 18 (279,489 tons/year).

The large bedload supply to Pool 20 (Figure 5-25), may be depositing in Pools 24, 25, and 26, where dredging amounts are far in excess of bed load supply. Although, it appears in the figure that an approximate balance exists between the bed load supply and dredging in Pool 26, a significant imbalance is believed to occur. As seen in Appendix C for Pool 26, the locations of historic dredging activities in Pool 26 are all located upstream of the confluence with the Illinois River, the primary tributary bed load supply to the pool. The bed load of the Illinois River is therefore likely transported downstream into the Open River segment of the UMR. Hence, the excess dredging in Pools 24-26 is most likely explained by the bed load of the Des Moines River being flushed through the relative steeper reach of Pools 20-22 into Pools 24-26. However, the dredging amounts in Pools 24-26 are almost two times the estimated bed load supply of the Des Moines River. As discussed in Section 5.6, the imbalance is explained by bed load sediments supplied by erosion of the main channel in lower Pool 19 and Pools 20, 21, 22, and 24 during recent decades.

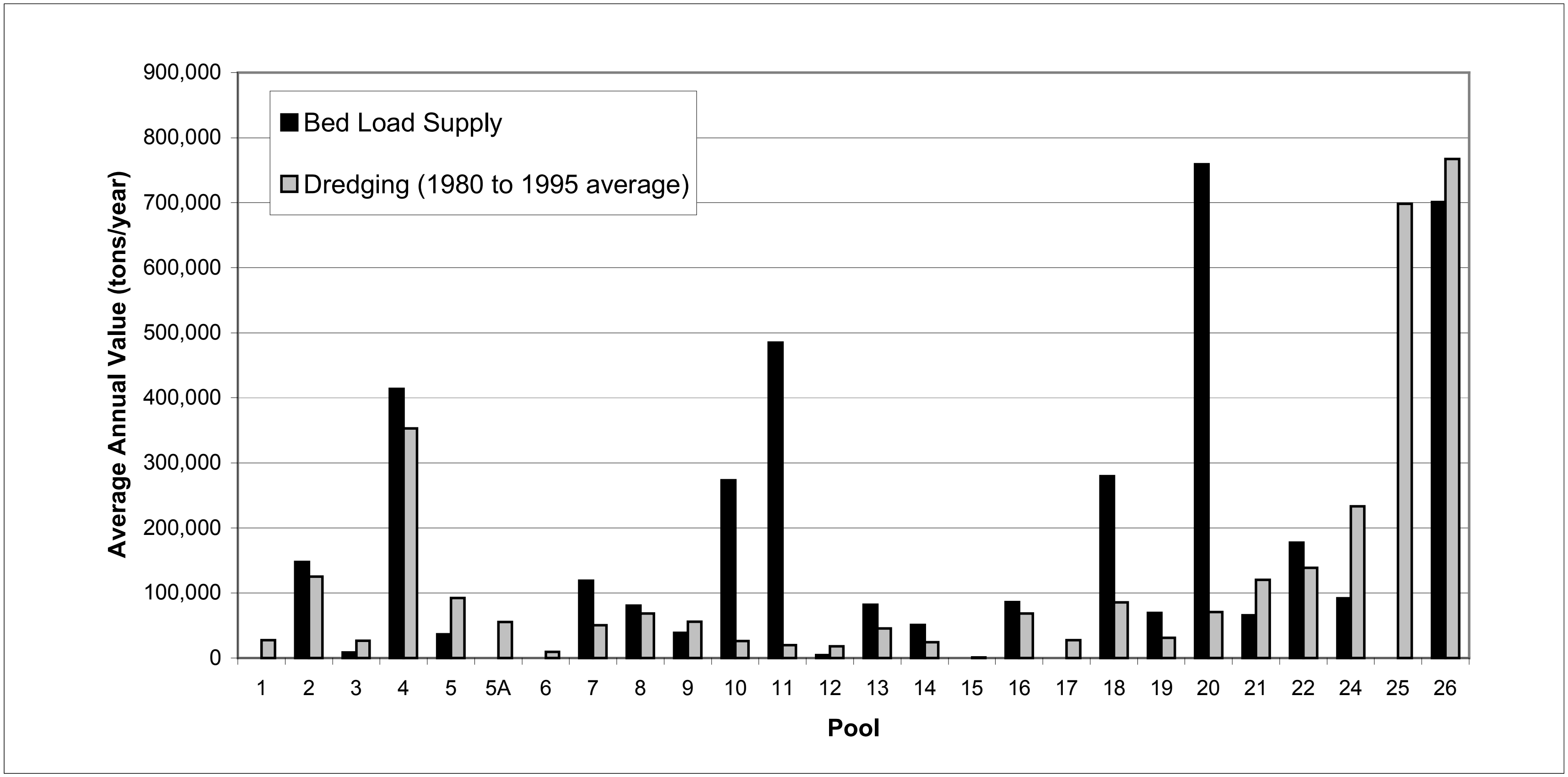


Figure 5-25: Comparison of average annual tributary bed load sediment supply to average annual dredging amounts along the UMR.

5.4.5 Levees

The locations of levee districts along the UMR and IWW are plotted on the set of maps presented in Appendix C (Scientific Assessment and Strategy Team, 1995). An example of these maps is shown in Figure 5-24. As seen from the maps, the density and encroachment of levees generally increases in a downstream direction along the UMR. Most of the levee districts shown on the maps in Appendix C were built in the 1960s and 1970s. Although not shown on the maps presented in Appendix C, railroad and highway embankments often act as levees along the UMR. In most cases, railroad embankments were constructed well before the 9-ft Channel Project.

Levee districts along the UMR serve various purposes, including flood control and wildlife refuges. In many cases, levees isolate the floodplain from the main channel of the UMR, reducing the area available for temporary storage of floodwater or deposition of sediment. Simons et al (1974) demonstrated that water stages at St. Louis, for the same discharge, increased significantly over the period of 1881 to 1973. The increased stage was attributed to reductions in bank-full channel capacity caused by the construction of rock and pile dikes and constriction of the floodplain caused by levees.

5.4.6 Watershed Reservoirs

Assessment of the timing and location of reservoir construction in the UMR watershed is necessary to understand downstream geomorphic changes. Reservoir construction in watershed areas of the UMR can have several physical impacts. These include alteration of downstream hydrology, storage of sediments eroded from upstream watershed areas and reduction of sediment supplies to downstream reaches. The impact of watershed reservoirs will be reflected in historic and future cumulative effects of the 9-ft Channel Project.

The 9-ft Channel Project includes 29 dams and pools along the UMR mainstem and 8 dams and pools along the IWW. To characterize the significance of those dams and pools, information on other dam and reservoirs in the UMR watershed was collected and evaluated. A database maintained by the USGS (USGS, 1990) was identified which includes the location and selected characteristics of reservoirs and controlled natural lakes that have normal capacities of at least 5,000 acre-feet or maximum capacities of at least 25,000 acre-feet and that were completed as of 1 January 1988. Evaluation of that database indicates that a total of 266 dams and reservoirs are contained within the UMR watershed, excluding the Missouri River basin. The dams and pools of the 9-ft Channel Project within the study area represent about 13 percent of the total number of reservoirs in the UMR basin.

As an example of the influence of reservoir construction, suspended sediment transport measurements for two tributaries are shown in Figure 5-26. The figure shows the influence of the Red Rock Dam, built in 1969, on suspended sediment transport along the Des Moines River at Tracy, Iowa, which is downstream of the dam. Also shown in the figure is the influence of Coralville Dam, which was built in 1958, on suspended sediment transport along the Iowa River at Iowa City. A decrease in suspended sediment transport as a result of dam construction is clearly observable from the data.

The distribution of reservoirs within the UMR watershed is shown in Figure 5-27. As seen in the figure, reservoirs are located on almost every major tributary to the UMR. Most of the tributaries have several reservoirs located along them. An evaluation of the total drainage area controlled by reservoirs on specific tributaries was not possible with the available data.

An evaluation was conducted of the year in which each reservoir in the UMR began operation. The result of that analysis is shown in Figure 5-28. As seen in the figure, reservoir construction in the basin increased very gradually over the period 1850 to 1909. About 80 percent of all the reservoirs in the UMR basin were constructed during the period of 1930 to 1989. Of that amount, about 40 percent of the reservoirs were constructed from 1930 to 1939, the same period during which the Nine-Foot Channel Project was constructed and impoundment within the navigation pools began.

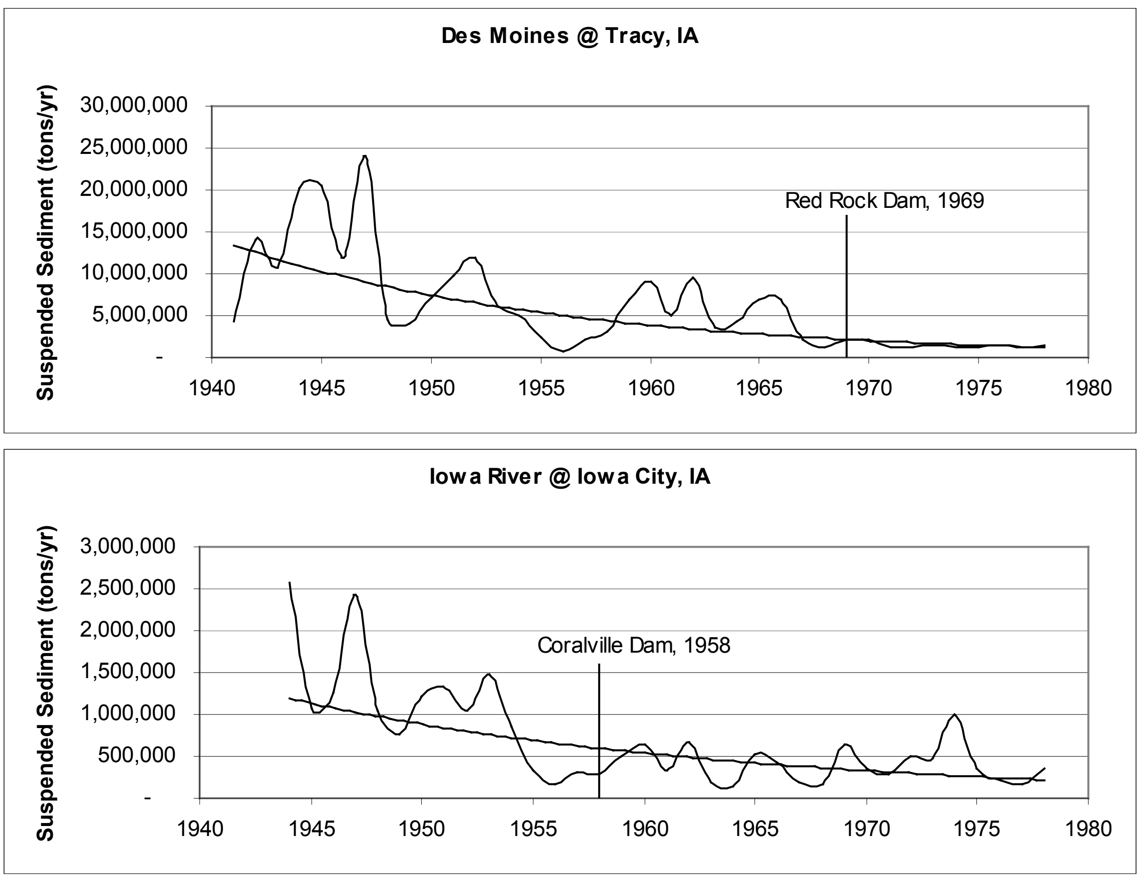


Figure 5-26: Example of influence of reservoirs on sediment transport of tributaries (USACE, 1981).

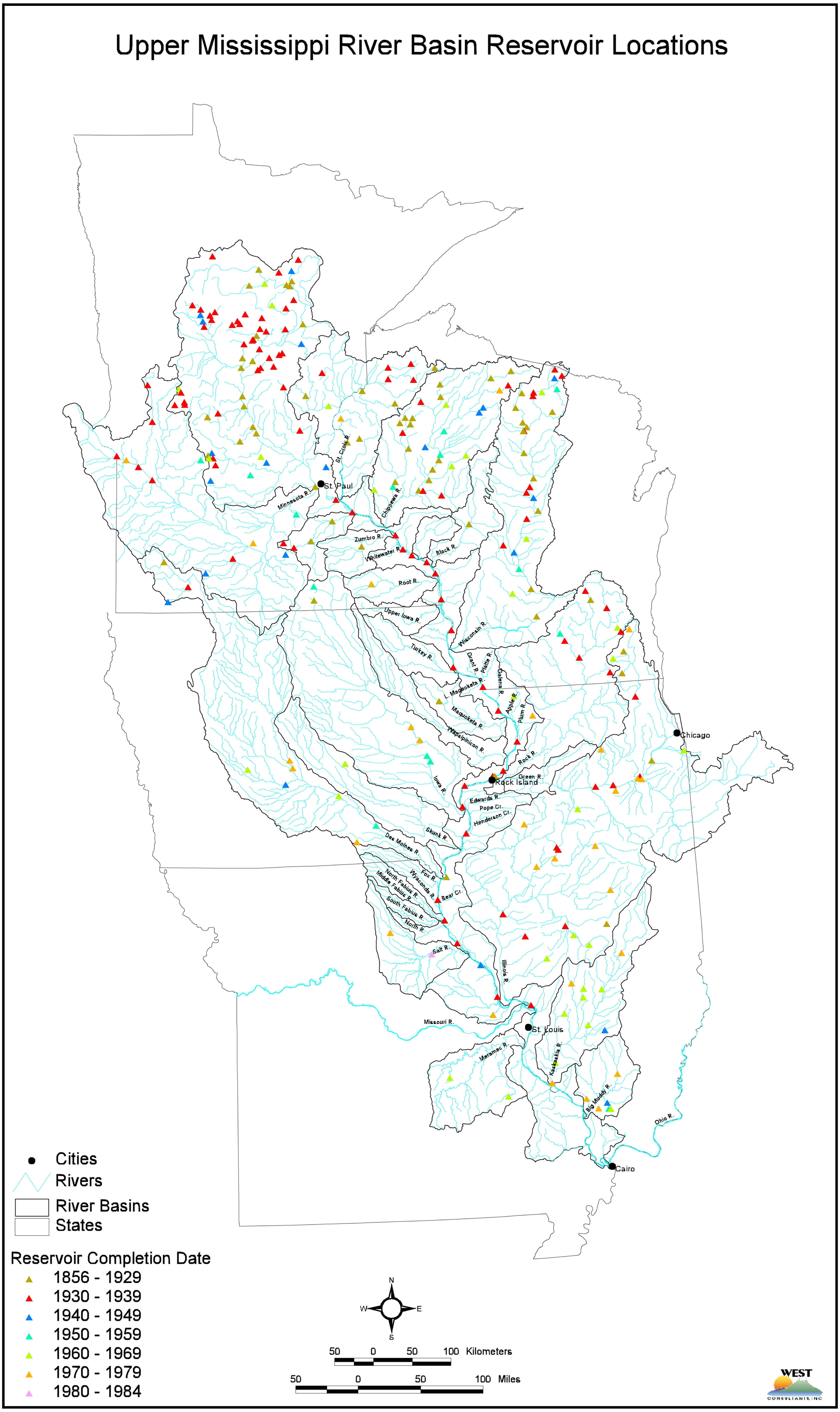


Figure 5-27: Spatial distribution of Reservoirs for the UMR basin (U.S. Geological Survey, 1990).

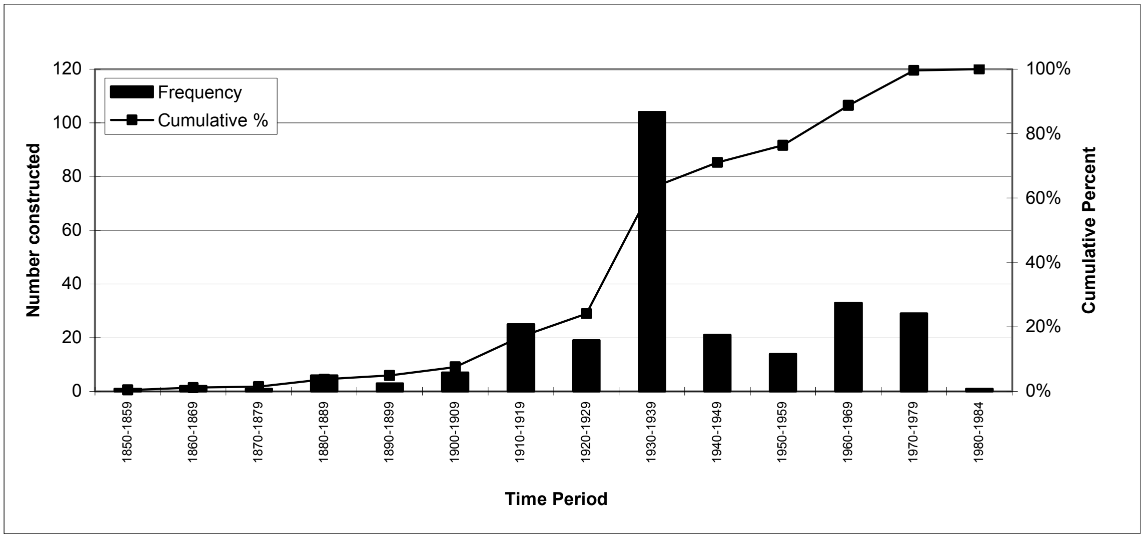


Figure 5-28: History of reservoir construction within the UMR study area (U.S. Geological Survey, 1990).

The impact of constructing numerous large reservoirs within the UMR basin is reflected in the results of the sediment budget analysis presented in Chapter 6. That analysis shows that tributary sediment supply to the mainstem UMR has been reduced by about 45 percent since construction of the Nine-Foot Channel Project. The trapping of sediment in the numerous watershed reservoirs, in combination with improved watershed land management practices, is likely responsible for this condition.

As described in Section 5.6, in the early decades after impoundment a condition of overall aggradation is observed in historic cross section data of the UMR. For recent decades, the data indicate that the trend has changed to slight overall erosion along the main channel bed. Similarly, the sediment budget analysis indicates that deposition rates in the backwater areas along the UMR have decreased when comparing the results for the time periods from immediate post-impoundment to 1950s and 1950s to 1995.

Furthermore, the reduction in historic sediment supplies to the UMR is probably also responsible for the general overall decrease observed in the amount of material dredged annually along the UMR since completion of the Nine-Foot Channel Project (See Figure 5-20). As discussed in Section 5.4.4, the average amount of sediment dredged per year has decreased in almost every pool along the UMR. In some cases, the decrease has been by an order of magnitude.

5.5 PLAN FORM ANALYSIS

An analysis of channel plan form evolution along the UMR and IWW was conducted. The objective of the analyses were to identify the historic changes in channel plan form that have occurred, identify the underlying geomorphic processes and to quantify the magnitude and rate of the change. The results of the plan form analysis are used as a basis for predicting future geomorphic conditions. The predictions are presented in Chapter 7.

5.5.1 Methods

Evaluation methods were chosen based on the available record of historic data, the characteristics of the navigation system, and consideration of prior studies of channel geomorphology for the project area. Generally, the plan form evaluation involved the identification and characterization of geomorphic features from a historic sequence of plan form data. The collected data was evaluated to identify patterns and trends in plan form change.

The specific plan form features evaluated were selected to meet the data requirements for estimation of future channel conditions and later assessment of ecological impacts. Definitions for the channel features were developed to allow consistent delineation and to facilitate technical discussion. The developed definitions are modifications of hydraulic classes for aquatic areas originally developed by the WES (WES, unpublished).

The definitions of plan form features employed in this study are:

Main Channel - The main channel of the river conveys the majority of discharge. Boundaries of the main channel are the apparent shorelines (i.e., land/water boundaries visible from aerial photographs of the river for average river flow conditions), straight lines across the mouths of secondary, tertiary, and tributary channels, and the outer boundary of inundated open-water areas upstream of locks. In most reaches, the main channel encompasses the navigation channel.

Secondary Channels - Secondary channels were defined as waterways that are directly connected to the main channel and have a minimum width 150 feet. A secondary channel will have a definitive entrance and exit and may contain submerged closure structures under average flow conditions.

Contiguous Backwater - Contiguous backwaters are off-main channel areas that include impounded areas, backwater lakes, and tertiary channels of less than 150 feet minimum width under average flow conditions. The contiguous backwaters have inlets and/or outlets to the main channel.

Isolated Backwater - These areas are located adjacent to the main channel, but lack an inlet and outlet to the main channel.

Islands - Islands were defined as discrete vegetated land areas isolated by open water.

A range of historic information was used in the identification of plan form features. The available plan form information included topographic maps, aerial photography, and Geographical Information System (GIS) coverages. Efforts were made to identify plan form data at four general points in time, 1930 (pre-Lock and Dam Era), 1940 (beginning of Post-Lock and Dam Era), 1975 (intermediate point), and 1989 (current conditions). A summary of the available plan form data sets is shown in Table 5-8. Generally, limited historic plan form data was found for the Open River section of the UMR and the entire Illinois River.

Each set of historic plan form data was converted to a common scale of 1:12,000 for evaluation. On a pool by pool basis, channel features were delineated and measured for each historic data set. The area of each delineated feature was measured with a digital planimeter. The width of the main channel at each river mile throughout each pool and the perimeter of each island were also measured.

In the preliminary review of historic plan form data, it was qualitatively recognized that plan form characteristics in the downstream 1/3 of each pool (Lower Pool) differ from those in the upstream 2/3 of each pool (Upper Pool). To allow evaluation of the noted differences, plan form features measured in approximately the lower 1/3 (Lower Pool) of each pool were differentiated from those measured in the upper 2/3 (Upper Pool) of each pool. The division between the upper and lower pool was set approximately at the upstream extent of the impoundment influence from the dam in each pool. This allows evaluation of the data for two different regions in each pool. This data organization would be useful if it is determined that there are different ecological conditions for the two portions of the pool. It is also noted that the LTRMP system (see following section) categorized all contiguous backwaters in the lower pool as impounded. Therefore, the backwaters in the lower pool in the current study correspond approximately to the impounded areas in the LTRMP classification. Summation of the features measured for the upper and lower pool provide details for the entire pool.

5.5.1.1 Plan Form Measurement Procedures

The main purpose of the plan form analysis was to characterize historic changes in channel morphology along the UMR and the IWW. Results of the analysis were used to identify trends in the historic changes to aquatic areas. As presented in Chapter 7, the identified trends are used for projecting future channel conditions.

A classification system for the UMR was developed by the Environmental Management Technical Center (EMTC) that focuses on land cover and land use of the river. This system was used by EMTC to classify 1989 data for the river. A second classification system, Hydraulic Classes for Aquatic Areas, was developed by Waterway Experiment Station (WES) (WES, unpublished). The WES classification system was also applied to the 1989 data set. The WES classification system is concerned with hydraulic features of the river. It is based on a simplification of a classification system published by Wilcox

(1993) as part of the Long Term Resource Monitoring Program (LTRMP). The LTRMP classification system is shown in the first column of Figure 5-29 and the WES system is shown in the second column. The LTRMP classifications are much more detailed than the WES classifications. However, the two primary levels of classification are the same for both the LTRMP and WES systems. The WES system simplifies the details regarding the secondary and tertiary levels of the classification.

The historic data available for use in the current study (WEST) do not allow the detailed delineation performed in the Land Cover/Land Use EMTC study nor do they serve the purpose of the this study. The current study uses the WES classification system with small modifications as discussed below. It is not possible to use the more detailed system proposed by Wilcox (1993). This is due to the fact that available historic data are in the form of black and white aerial photographs. Infrared photographs and other data used in the EMTC 1989 classification are not available for the historic period considered in the current study. Furthermore, field trips to areas where more data were needed were conducted as part of the 1989 EMTC classification effort. It is, of course, not possible to field verify historic photographs. By necessity, the current study used the WES classification system with modifications. WES delineated the main channel into navigation channel and channel border by simply subtracting a 300 ft wide strip (500 ft wide in bends) from the area of the main channel. This method was not appropriate for the current study. Tributary channels were also not considered in the current study because the aerial photographs did not have consistent coverage of these areas. Contiguous backwaters were also not divided into two groups. Islands were added to the WEST classifications, as they are important geomorphic features of the river. The WEST classification is shown in the third column of Figure 5-29.

In addition to the issues discussed in the previous paragraph, it is important to note that the results of different delineation efforts will always reflect the definitions and interpretation procedures used. Therefore, the reader should not simply compare the reported values to the results derived from other data, developed by different delineation methods. The delineation of aquatic features from identical data sets, even for total water area, is not straightforward for many reasons. For example, tributaries may not be included in the delineation. The upstream point along a tributary to which delineation is made may not be consistent. The minimum size of aquatic area that can be defined or measured may be different. Also, the area behind a levee may or may not be included in the total water area. Further, the time period considered may not cover the same area of the pool. These are some of the issues that need to be considered before results of different delineation efforts can be compared. When, for example, area of secondary channels is compared between different delineation efforts, even more issues need to be addressed. An example could be the distinction between secondary channel and backwater. Also, even though a secondary channel may be identified at the same location on two coverages, the exact boundary between the secondary channel and backwater or main channel may be interpreted to be slightly different. To ensure consistent delineation procedures, and consistency in the analysis of different timeframes, these and other issues were carefully addressed in the current delineation effort. For the same reasons, a direct comparison of results between two delineation efforts based on different classification schemes, delineated by different groups of people, is not reasonable.

The data used in the plan form analysis were from various sources; including aerial photography, topographic maps and Geographical Information System (GIS) coverages. Several issues regarding the quality of the data were evaluated in order to assure the consistency of the data set. All data were processed to a consistent scale, 1:12,000, before being measured. This was especially important for the aerial photography, which originally was of various scales. Converting the data to a common scale enhances the consistency of resolution between the data sets. The photographic quality of the aerial photographs varied due to different lighting conditions at the time the pictures were taken. Overall, this was deemed a minor problem. Water stage in the river at the time the data were taken was of importance for consistency. In Appendix I, the stages associated with the date of each data set are listed. In general, the stage was found to be in a narrow range, which is to be expected as the data sets are for a similar time of the year and the river is regulated by Lock and Dams. Most of the aerial photos were taken in the fall, so differences in vegetation coverage should be limited. However, in some cases, the aerial photos were acquired at a different time of the year (see Appendix I) and that could influence the results. Only the GIS data (1989) is geo-referenced, so a direct overlay comparison was not possible. Therefore, comparing independent measurements for each data set was necessary. For the 1989 data set, the following categories were delineated as water after discussion with EMTC, the creator of the 1989 GIS layer: open water, submergents, submergents-rooted floating aquatics, submergents-rooted floating aquatics-emergents, rooted floating aquatics and rooted floating aquatics-emergents. Overall, the influence of these limitations was found to be small and the trend of changes developed from the plan form data was not affected by these limitations.

In order to assess the error in the plan form measurements for the current study, the 1989 plan form data were compared to the GIS 1989 Land Cover/Land Use that formed the background for our measurements. The total water area for the GIS 1989 Land Cover/Land Use was adjusted to match the coverage measured in the current study. Then the total area was calculated and compared to data obtained in the current study. The results of this comparison are presented in Table 5-7. The error (percent difference) between the total water area of the adjusted EMTC coverage and the WEST aquatic areas ranges between 0.01 and 1.29 percent for all of the pools. The average error for all the pools is about 0.55 percent. This magnitude of error is acceptable for the purpose of the study.

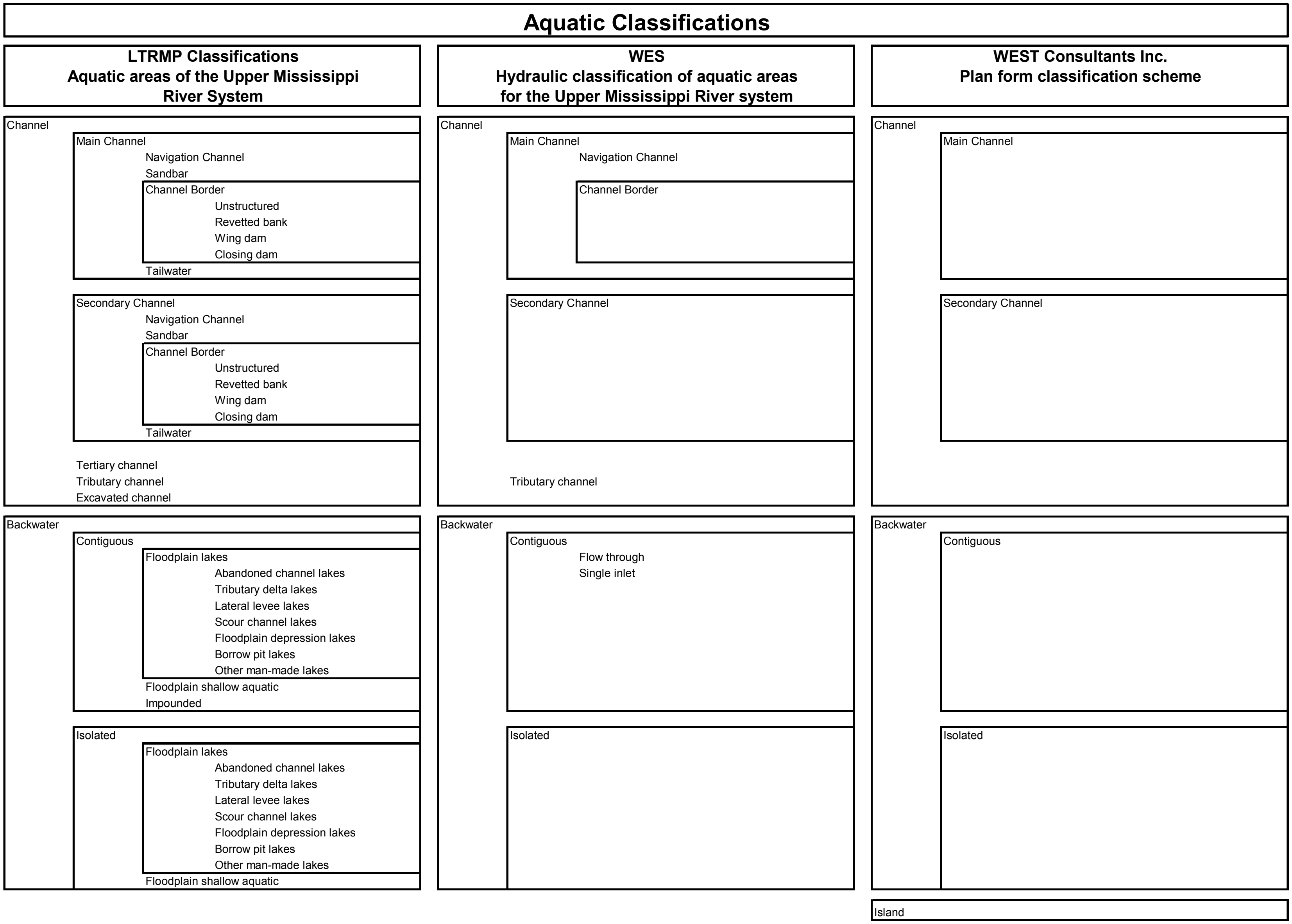


Figure 5-29: Classification Schemes.

Table 5-7: Error estimates associated with plan form measurements.

Pool	WEST Measured Total Water Area (acre)	EMTC Adjusted Total Water Area (acre)	Difference (Error) (%)
4	34,504	34,613	-0.31%
5	10,213	10,216	-0.03%
5A	5,622	5,696	-1.29%
6	8,713	8,722	-0.11%
7	12,629	12,724	-0.75%
8	20,250	20,436	-0.91%
9	27,266	27,025	0.89%
10	15,383	15,411	-0.18%
11	19,307	19,144	0.85%
12	10,934	11,017	-0.75%
13	22,906	23,112	-0.89%
14	9,621	9,638	-0.17%
15	3,503	3,523	-0.56%
16	10,989	11,105	-1.05%
17	6,487	6,464	0.36%
18	11,091	11,176	-0.76%
19	27,373	27,518	-0.53%
20	7,195	7,216	-0.29%
21	7,118	7,129	-0.15%
22	7,530	7,627	-1.27%
24	10,614	10,578	0.34%
25	14,712	14,689	0.16%
26	16,515	16,516	-0.01%
Average Error			0.55%

Table 5-8: Summary of available plan form data for Upper Mississippi River and Illinois River.

Upper Mississippi River

District	Pool	Timeframe 1930	1940	1975	1989
St. Paul	4	30		75	89
	5	30		73	89
	5A	30		73	89
	6	30		73	89
	7	30		73	89
	8	30		73	89
	9	30		73	89
	10	30		73	89
Rock Island	11	30	49	75	89
	12	30	40	75	89
	13	30		75	89
	14	30	51	75	89
	15	30	37	75	89
	16	30		75	89
	17	30	41	75	89
	18	30	41	75	89
	19[1]	30	40	75	89
	20	30		75	89
	21	30		75	89
	22	30		75	89
St. Louis	24	30			89
	25	30			89
	26[2]	30		75	89

Illinois Waterway

Pool	1994
Alton	94
LA Grange	94
Peoria	94
Starved Rock	94
Marseilles	94
Dresden Is.	94

30 Plan form data available and actual year photography taken

(dark cell) No usable plan form data available

[1]Data is for post-dam condition in 1930

[2]Downstream 8 miles of the Pool are missing for 1930

Note: Arial photography for 1940 for Pools 4-10 was included in the appendices but not used as the quality was not high enough.

5.5.2 Results for Upper Mississippi River

Table 5-8 shows the plan form data that were available and used in the study. The plan form data were obtained from various sources as discussed in previous section. As is seen in the table, data were not available for all time frames.

5.5.2.1 Plan Form Data for Upper Mississippi

Different data were obtained for each aquatic class, depending on the nature of the class. The following statistics were measured or developed for the upper and lower portion of each pool:

Main channel: Area, width, and mean width.

Secondary channels: Area, number, mean area, and median area.

Contiguous backwaters: Area, number, mean area, and median area.

Isolated backwater: Area, number, mean area, and median area.

Islands: Area, number, perimeter, mean area, median area, mean perimeter, and median perimeter.

Approximately 25,000 individual features were identified, delineated, and measured as part of the plan form analysis for Pools 4 through 26. An example of the developed plan form data is shown in Figure 5-30 to Figure 5-32 for Pool 4. In Appendix F the data for all the pools are presented both graphically and in tabular form. To facilitate data analysis and review, summaries of the plan form data were developed and plotted as profiles along the UMR. The developed plots are shown in Figure 5-35 to Figure 5-40.

Using the developed historic plan form statistics, the available historical plan form photography and maps were carefully inspected to identify concentrated areas of geomorphic change. A map of each pool was developed which summarizes the concentrated areas of historic change identified over the available period of record. The concentrated areas of plan form change were grouped into nine general categories of geomorphic processes. As denoted on the maps of historic plan form change, the categories of geomorphic processes are:

- Loss of Contiguous Backwaters
- Filling of Isolated Backwaters
- Loss of Secondary Channels
- Filling between Wing Dams
- Wind-Wave Erosion of Islands
- Island Dissection
- Tributary Delta Formation
- Delta Formation
- Island Formation

An example of the developed maps for Pool 20 is shown in Figure 5-33. The maps for all the pools are presented in Appendix E. Typical examples for of the nine geomorphic process delineated on the maps of historic changes are summarized in Section 0. A summary of the historic processes observed in each pool is shown in Table 5-9 lists what processes were observed historically in each pool. Wind-wave erosion includes all instances of island erosion identified. Specific causes of island erosion could not be determined by the evaluation of historic plan form information. The Board of Consultants was involved in the identification and characterization of the geomorphic processes. It was determined that the term wind-wave erosion was the best overall characterization. It is noted that for several pools, concentrated areas of geomorphic change were not identified. However, it is important to recognize that measured changes in aquatic classes may still be significant.

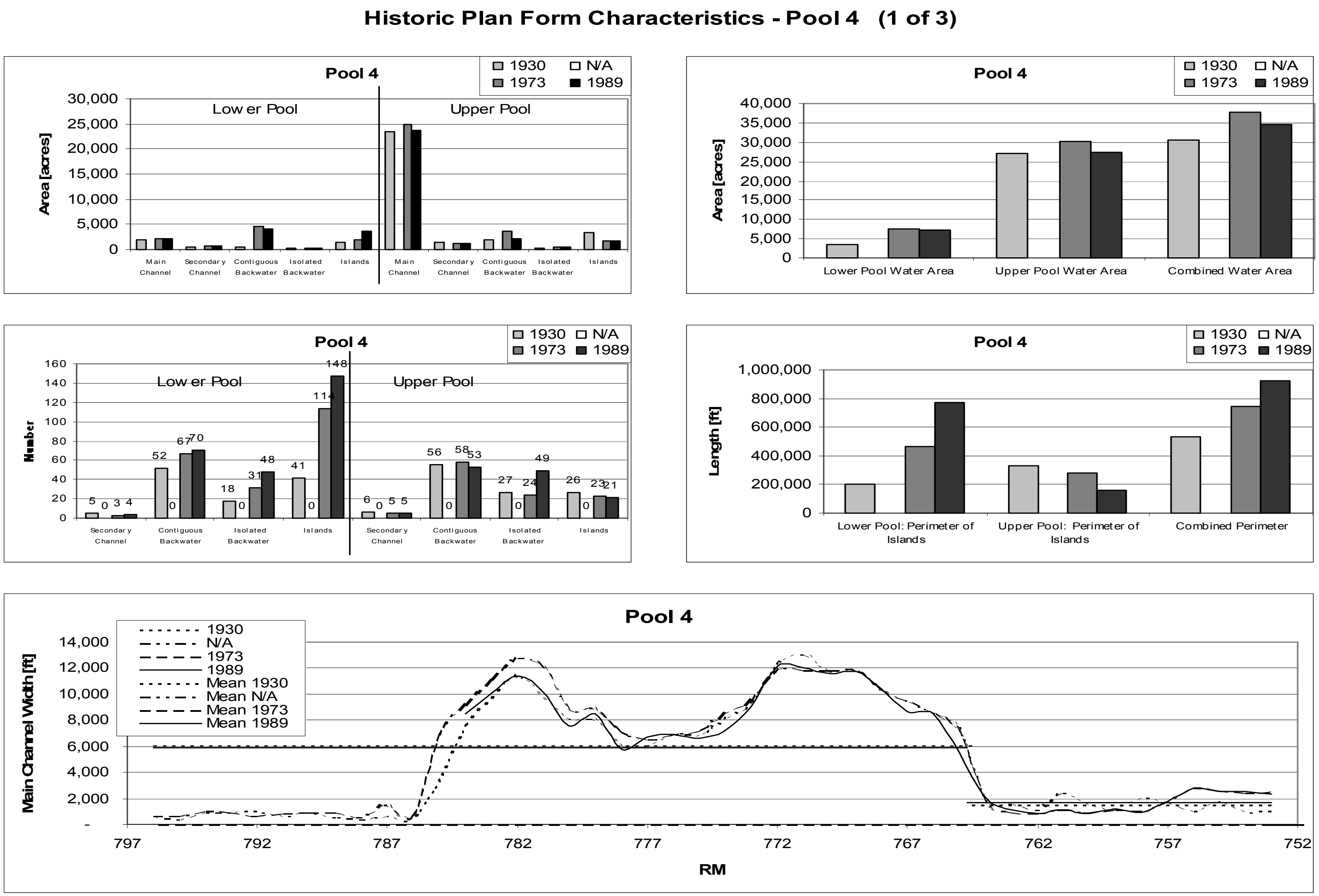


Figure 5-30: Example of statistics developed from the plan form analysis. (Data for all pools are presented in Appendix E).

Historic Plan Form Characteristics - Pool 4 (2 of 3)

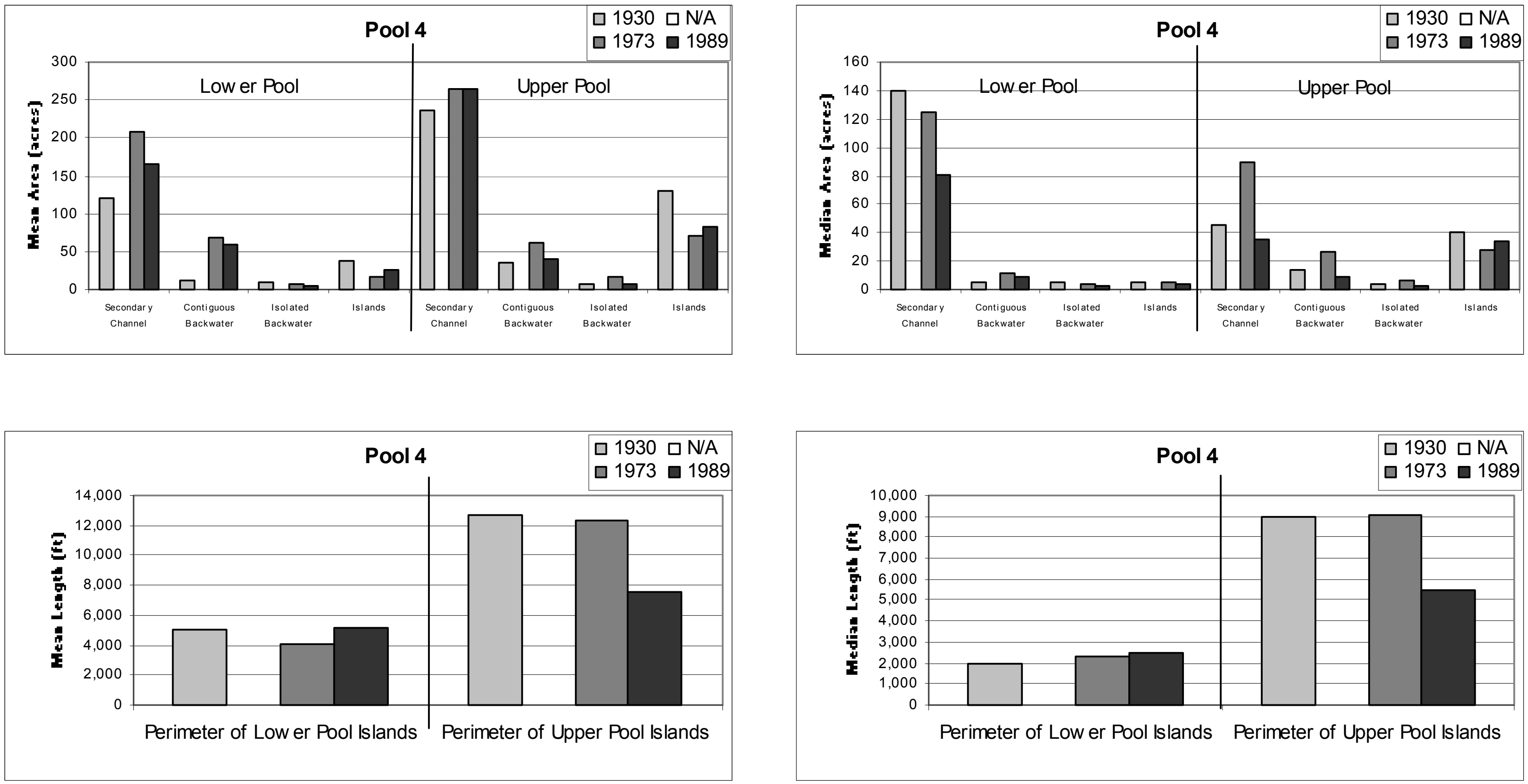


Figure 5-31: Example of statistics developed from the plan form analysis. (Data for all pools are presented in Appendix E).

Historic Plan Form Characteristics - Pool 4 (3 of 3)

RM 764.7-752.8	Lower Pool						
	MC	SC	CB	IB	AI	PI	TOW
	acre	acre	acre	acre	acre	ft	acre
1930	2,011	603	604	151	1,562	204,750	3,369
1973	2,210	625	4,533	201	2,006	463,350	7,569
1989	2,230	659	4,054	189	3,718	768,400	7,132

RM 796.9-764.7	Upper Pool						
	MC	SC	CB	IB	AI	PI	TOW
	acre	acre	acre	acre	acre	ft	acre
1930	23,562	1,421	2,033	193	3,371	330,400	27,209
1973	24,963	1,324	3,612	420	1,654	283,300	30,319
1989	23,600	1,323	2,066	384	1,726	158,200	27,373

RM 796.9-752.8	Total Pool						
	MC	SC	CB	IB	AI	PI	TOW
	acre	acre	acre	acre	acre	ft	acre
1930	25,573	2,024	2,637	344	4,933	535,150	30,578
1973	27,173	1,949	8,145	621	3,660	746,650	37,888
1989	25,830	1,982	6,120	572	5,443	926,600	34,504

Lower Pool										
RM 764.7-752.8	Mean					Median				
	SC	CB	IB	AI	PI	SC	CB	IB	AI	PI
	acre	acre	acre	acre	ft	acre	acre	acre	acre	ft
1930	120.6	11.6	8.4	38.1	4,993.9	140.0	5.0	4.5	5.0	2,000
1973	208.3	67.7	6.5	17.6	4,064.5	125.0	11.0	3.6	5.0	2,300
1989	164.8	57.9	3.9	25.1	5,191.9	81.0	8.3	2.3	4.3	2,500

Upper Pool										
RM 796.9-764.7	Mean					Median				
	SC	CB	IB	AI	PI	SC	CB	IB	AI	PI
	acre	acre	acre	acre	ft	acre	acre	acre	acre	ft
1930	236.8	36.3	7.1	129.7	12,707.7	45.0	13.5	4.0	40.0	9,000.0
1973	264.8	62.3	17.5	71.9	12,317.4	89.0	26.0	6.5	28.0	9,100.0
1989	264.6	39.0	7.8	82.2	7,533.3	35.0	9.0	3.0	34.0	5,500.0

MC: Main Channel
SC: Secondary Channel
CB: Contiguous Backwater
IB: Isolated Backwater
AI: Area of Islands
PI: Perimeter of Islands
TOW: Total Open Water

Figure 5-32: Example of statistics developed from the plan form analysis. (Data for all pools are presented in Appendix E).

Table 5-9: Summary of historic dominant geomorphic processes identified within UMR Pools. The maps showing the location of these concentrated areas of change are in Appendix E.

Geomorphic Reach	Pool	Loss of Contiguous Backwater	Filling of Isolated Backwaters	Loss of Secondary Channels	Filling between Wing Dams	Wind-Wave Erosion of Islands	Island Dissection	Tributary Delta Formation	Delta Formation	Island Formation
2	4	■						■	■	
3	5					■				
	5A					■				
	6									
	7					■	■		■	
	8					■	■			
	9					■				
4	10	■								
	11	■						■		■
	12	■				■				■
	13									
5	14	■								
	15									
	16	■								
	17				■					
6	18	■			■	■				■
	19	■						■		
7	20	■			■					
	21	■			■					
	22	■								
8	24	■		■	■					
	25	■			■					
	26	■			■					
9	OR	■	■	■	■					
10	OR	■	■	■	■					

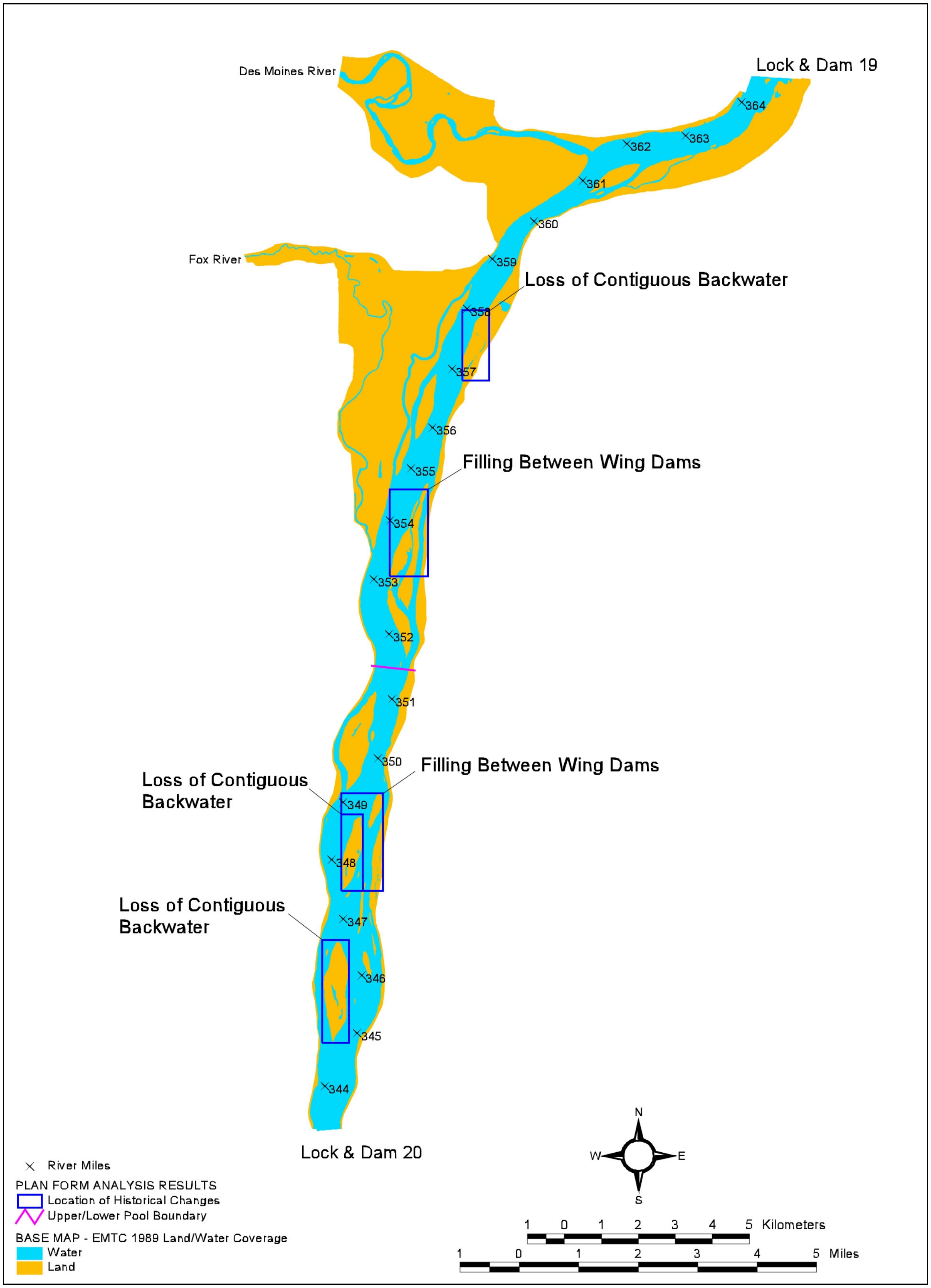


Figure 5-33: An example of maps showing observed geomorphic changes from the plan form data. Full sized figures for every pool along the UMR are shown in Appendix E.

5.5.2.2 Discussion

In Section 5.2 ten reaches of similar geomorphic characteristics were defined. In part, the reaches were defined by studying the plan form data presented in this section. The following discussion focuses on how the geomorphic conditions of each reach influence the plan form characteristics within each pool along the UMR. The geomorphic reaches are defined as:

Reach 1 – Pools 1-3
Reach 2 – Pool 4 (Lake Pepin)
Reach 3 – Pools 5 – 9
Reach 4 – Pools 10 – 13
Reach 5 – Pools 14 - 17
Reach 6 – Pools 18 - 19
Reach 7 – Pools 20 – 22
Reach 8 – Pools 24 – 26
Reach 9 – Below Pool 26 to Thebes Gap
Reach 10 – Thebes Gap to Ohio River confluence

Generally, the plots of historic plan form statistics for the UMR navigation pools demonstrate there are similarities between the pools contained within each geomorphic reach. However, it is also observed that each individual pool may have unique characteristics that are not necessarily shared by the other pools in the reach. The influence of local geologic controls, major tributaries, and watershed conditions may significantly affect the conditions in any single pool.

The plots of historic plan form statistics for the UMR pools show several trends in the aquatic characteristics of the river from upstream to downstream. Both contiguous and isolated backwater areas decrease in a downstream direction along the river. Downstream of Pool 14, the number and area of these aquatic classes are much smaller than upstream. Number and area of islands decreases similarly. Overall, this shows that the diversity of the river environment tends to decrease in a downstream direction.

In Figure 5-34 the main channel width of the UMR in 1989 is plotted for all the pools. The pools with the largest impounded areas are easily identified. It is observed that the main channel river width narrows in the downstream direction along the river. The broad width of Lake Pepin in Pool 4 is noted as primarily a natural impoundment created by the alluvial fan of the Chippewa River. Pool 19, another large impoundment, is noted as the oldest impoundment along the UMR study reach. Reaches 5 and 7 have uniform width due to the constraining influence of the local geology. A trend line for width plotted on the figure indicates that the river narrows in a downstream direction. If the wide areas created by the impoundment are not included, the trend is widening of the main channel in the downstream direction.

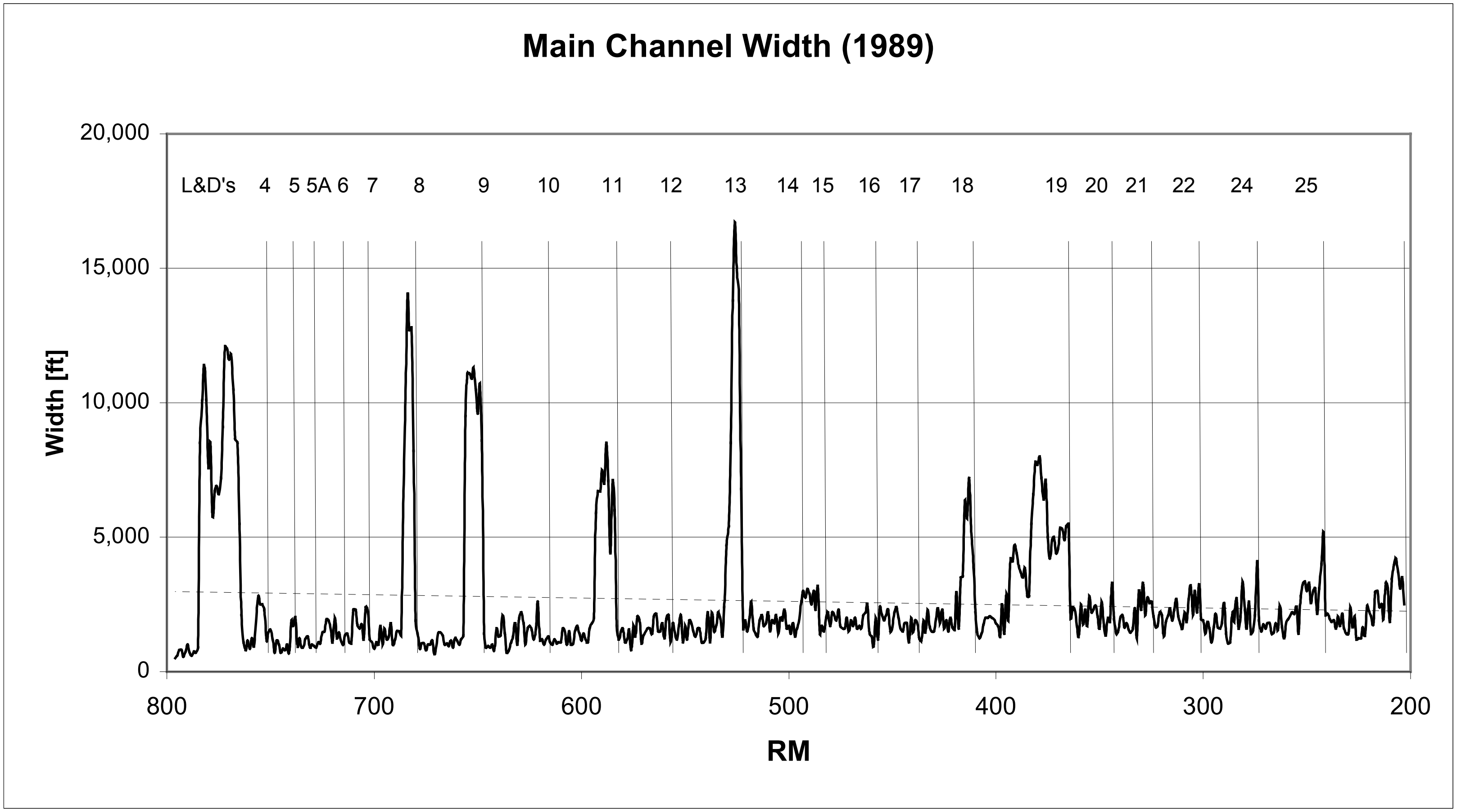


Figure 5-34: UMR main channel width every river mile measured from plan form data for the year 1989. The vertical lines represent the location of the locks and dams. The dashed line represents the linear trend for the width.

In Figure 5-35 the total water area is plotted for each pool. It is observed that Geomorphic Reaches 5 (Pools 14-17) and 7 (Pools 20-22) are the most stable since the construction of the locks and dams. It is also reflected in the small relative changes from pre-dam to post-dam time frames for these reaches. The stability is attributed to geologic control within these reaches. Figure 5-35 shows also that where 1940s data are available the total water area has in all cases decreased from immediate post-dam to present. The noted loss of water area is probably due to sedimentation. For Geomorphic Reach 3 (Pools 5-9) the total water area has increased from the mid-1970s to 1989. This is a reversal in the trend for water area in these pools compared to the conclusions of the GREAT-I study (1980) and Olson (1981) which were based on data from 1939-1973. In all of the Reach 3 pools, the open water is increasing in the lower pool due to erosion of islands (erosion of islands in Pool 8 is discussed in Section 5.5.5.4). However, it is likely that the bottom bathymetry is simplifying for these pools, especially in the lower windswept portions of the pools. The reversal in trend is probably due to decreasing sediment load from tributaries caused by better agricultural land use practices, systematic control of sediment supply from the Chippewa River, and the construction of dams on tributaries. The Chippewa River dominates the bed load in this reach of the river. Dredging in Pool 4 has likely influenced the balance between the sediment load needed to sustain and/or grow islands in this reach and eroding forces such as wind-wave action has been altered in these pools. It is also noted that as islands are lost, more open water is created potentially making remaining islands more vulnerable to erosion, as the wind fetch increases.

Decreasing trends for the area of both contiguous and isolated backwaters are observed in a downstream direction in Figure 5-36 and Figure 5-37. Similarly, Figure 5-38 shows that the number of isolated backwaters decreases in the downstream direction. Pool 15 has one of the smallest area of backwater of all the UMR pools. The area of backwater generally decreases downstream of Pool 15. This trend continues downstream of Lock and Dam 26. In the Open River segment of the UMR, aquatic classes are limited primarily to the main channel and a few secondary channels.

Figure 5-38 shows that the number of isolated backwaters in some pools is higher now than at any time in the post-locks and dams era, even though the total area of isolated backwater has decreased. This is probably due to contiguous backwaters being converted to isolated backwaters. This may occur when the inlet or outlet of a contiguous backwater is blocked by sedimentation. If the sedimentation process continues, it is reasonable to expect that the isolated backwater will eventually be lost.

A common perception for the UMR system is that the area of contiguous backwaters is decreasing. It is interesting to note that in several UMR pools the opposite holds true, the area of contiguous backwater is increasing. This is especially evident in Geomorphic Reach 3 (Pools 5 - 9). Similarly, the number of isolated backwaters are considerably higher today (1989) than they were before construction of the locks and dams system (1930).

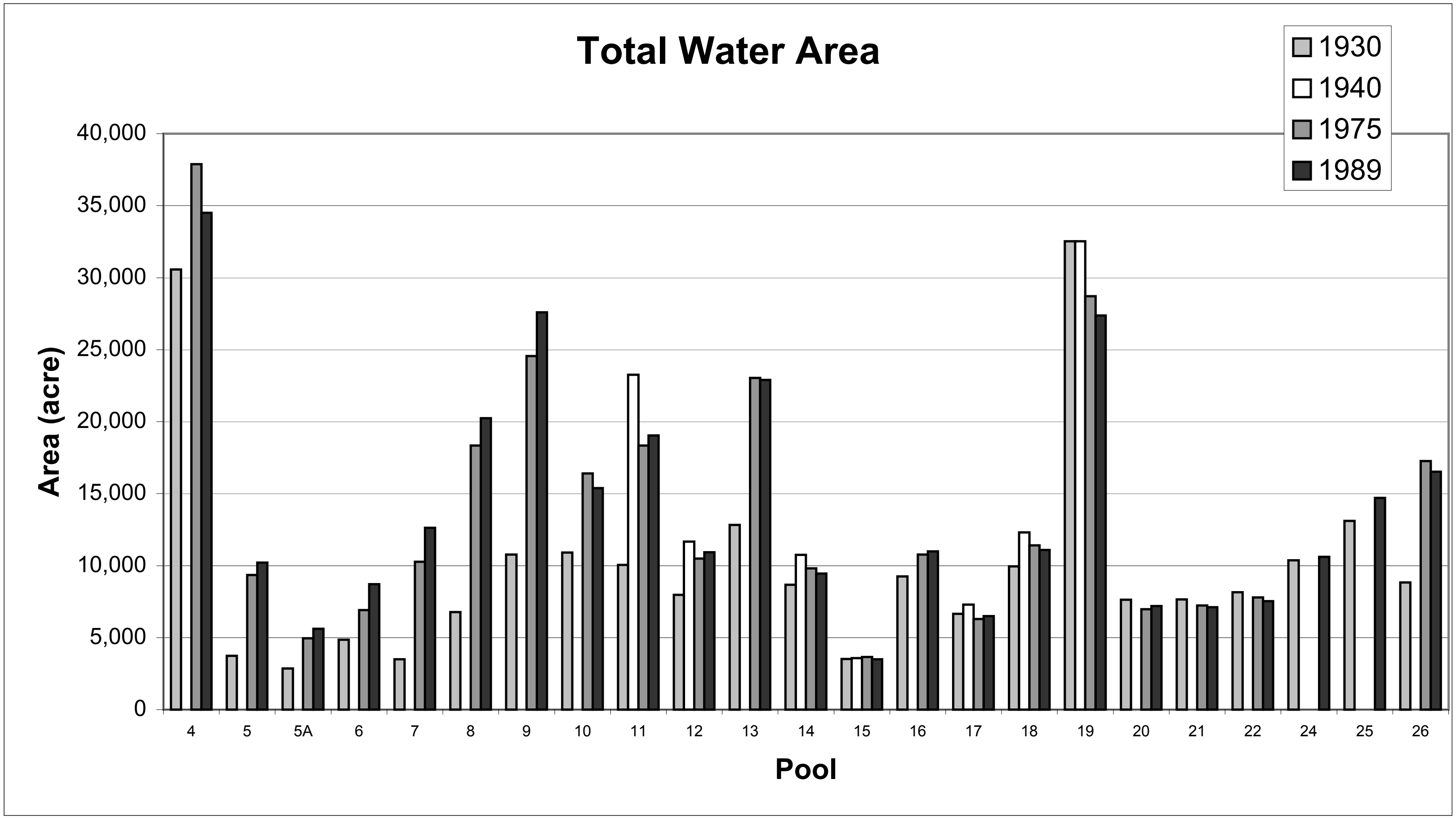


Figure 5-35: Water area, for every pool for the four time periods, measured from the plan form data. Missing columns represent data gaps in the coverage (the years in the legend represents timeframe, see Table 5-8 for actual years).

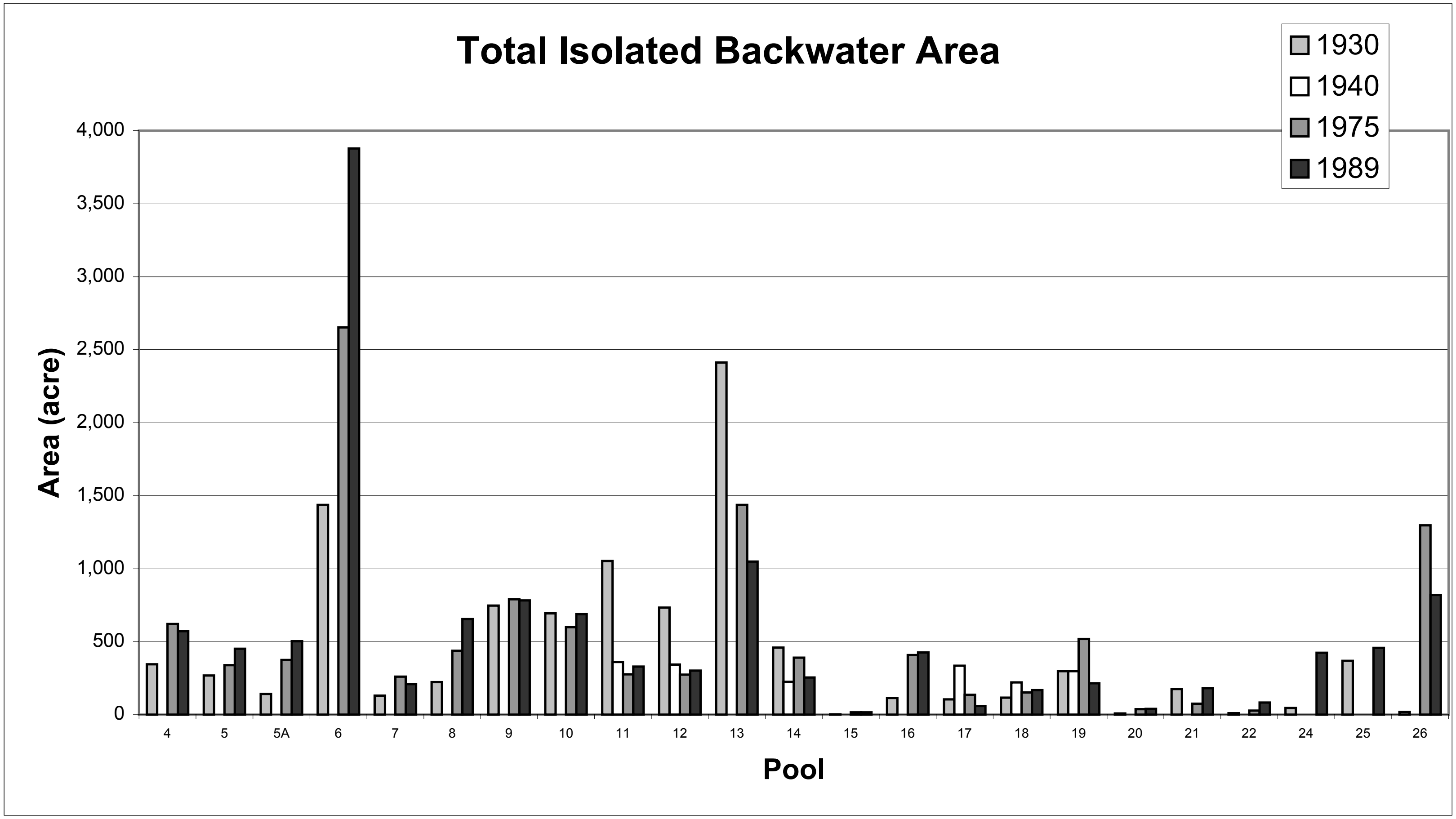


Figure 5-36: Area of isolated backwater, for every pool for the four time periods, measured from the plan form data. Missing columns represent data gaps in the coverage (the years in the legend represents timeframe, see Table 5-8 for actual years).

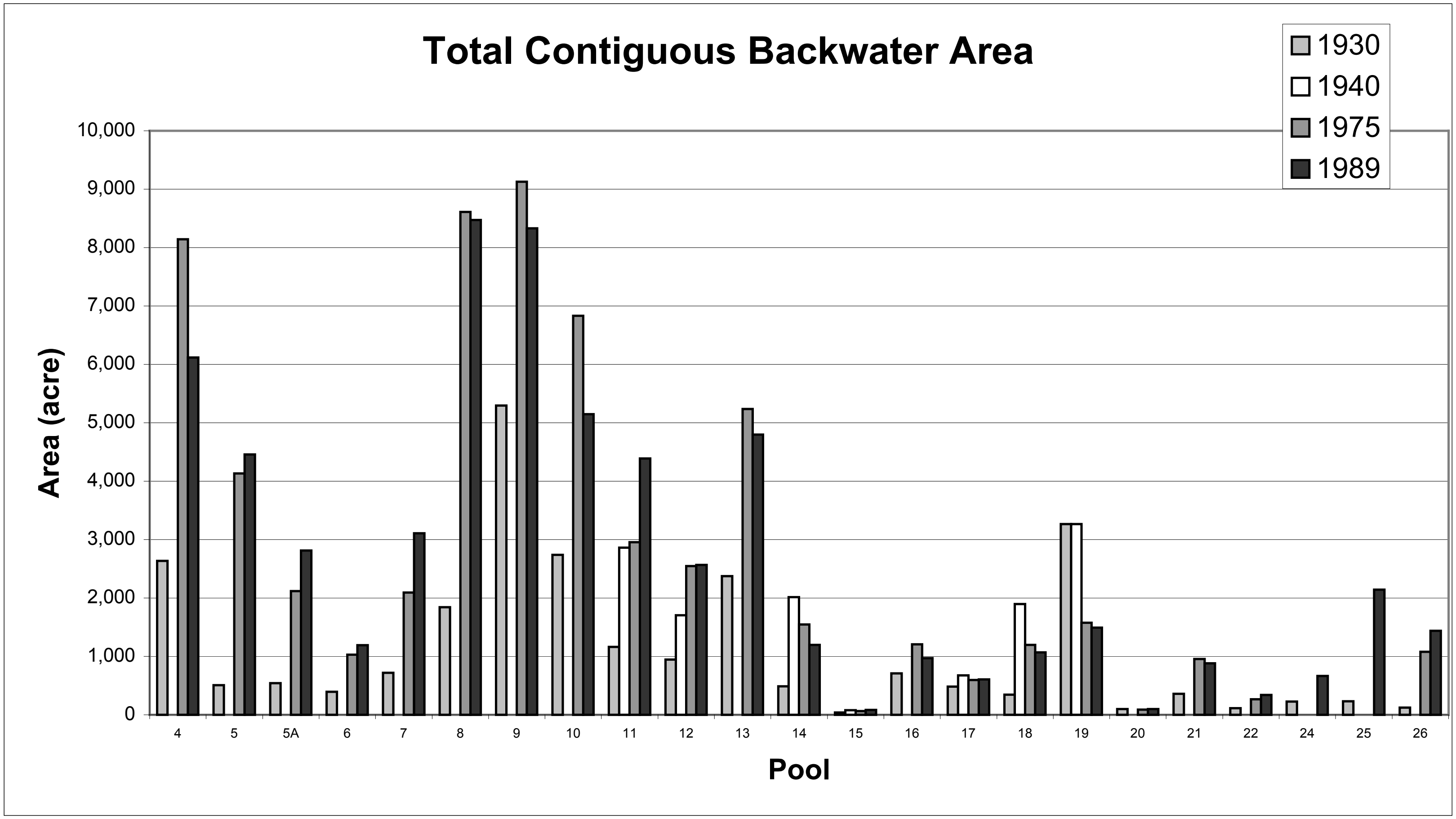


Figure 5-37: Area of contiguous backwater, for every pool for the four time periods, measured from the plan form data. Missing columns represent data gaps in the coverage (the years in the legend represents timeframe, see Table 5-8 for actual years).

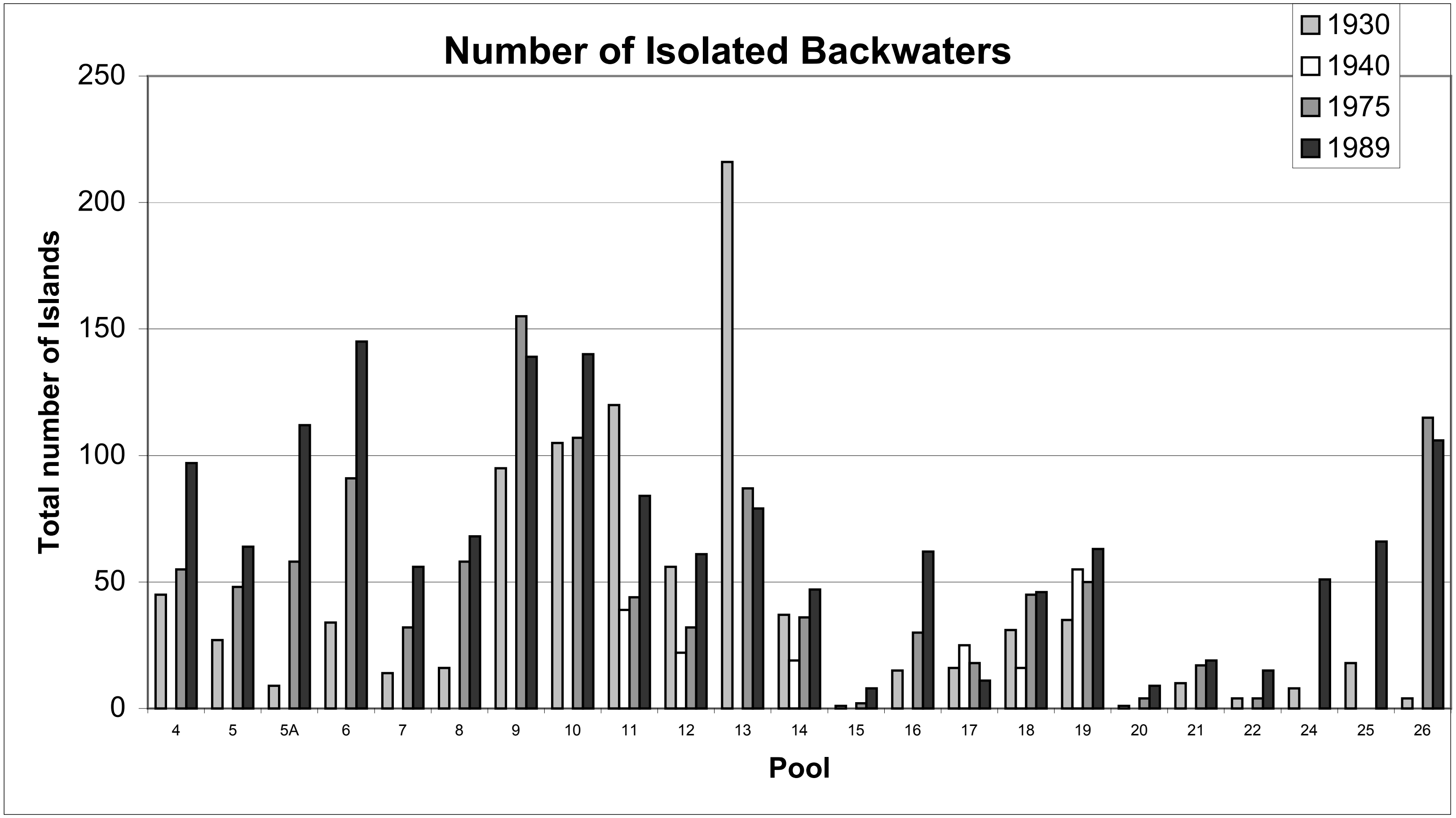


Figure 5-38: Number of isolated backwater, for every pool for the four time periods, measured from the plan form data. Missing columns represent data gaps in the coverage (the years in the legend represents timeframe, see Table 5-8 for actual years).

In Figure 5-39 and Figure 5-40 the historic area and number of islands within UMR pools is plotted. In most of the pools, the total area of islands has decreased over time during the post locks and dams era. However, the total number of islands has increased significantly in all pools between the mid-1970s and 1989, with the exception of Pools 13 and 19 through 26. Reaches 3 and 4 (Pools 5 through 13) have about 9.2 islands per river mile compared to 2.3 islands per river mile for Reaches 5 through 8 (Pools 14 through 26). There are several possible explanations for this large difference. First, the large bed load sediment supplies, which influence island formation and maintenance, enter the UMR from the Chippewa River in Pool 4, Wisconsin River in Pool 10, and Turkey River in Pool 11. Second, the UMR is much more constrained along the downstream reaches, both due to geologic controls and man-made constraints, such as wing dams and levees. It is also observed that the confluence of the Des Moines River, a large bed load contributor to the UMR, in Pool 20 does not contribute to a large jump in the number of islands downstream along the UMR. It is likely that the bed load supply of the Des Moines River is being transported through Pools 20, 21, 22 and 24. The slope of the reach is also greater than the average river slope (see Figure 5-57). It is also noted that dredging volumes substantially increase in Pools 25 and 26, which also suggests that the bed load supplies of the Des Moines River are indeed flushed downstream (see Section 5.4.4 for a detailed discussion on dredging).

The shape of islands along the UMR changes considerably from upstream to downstream. In upstream pools the shape of the islands are irregular with jagged edges. In downstream pools most islands have smooth land-water boundaries and are elongated. As shown in Figure 5-41, the median size of islands and island perimeter increases in a downstream direction.

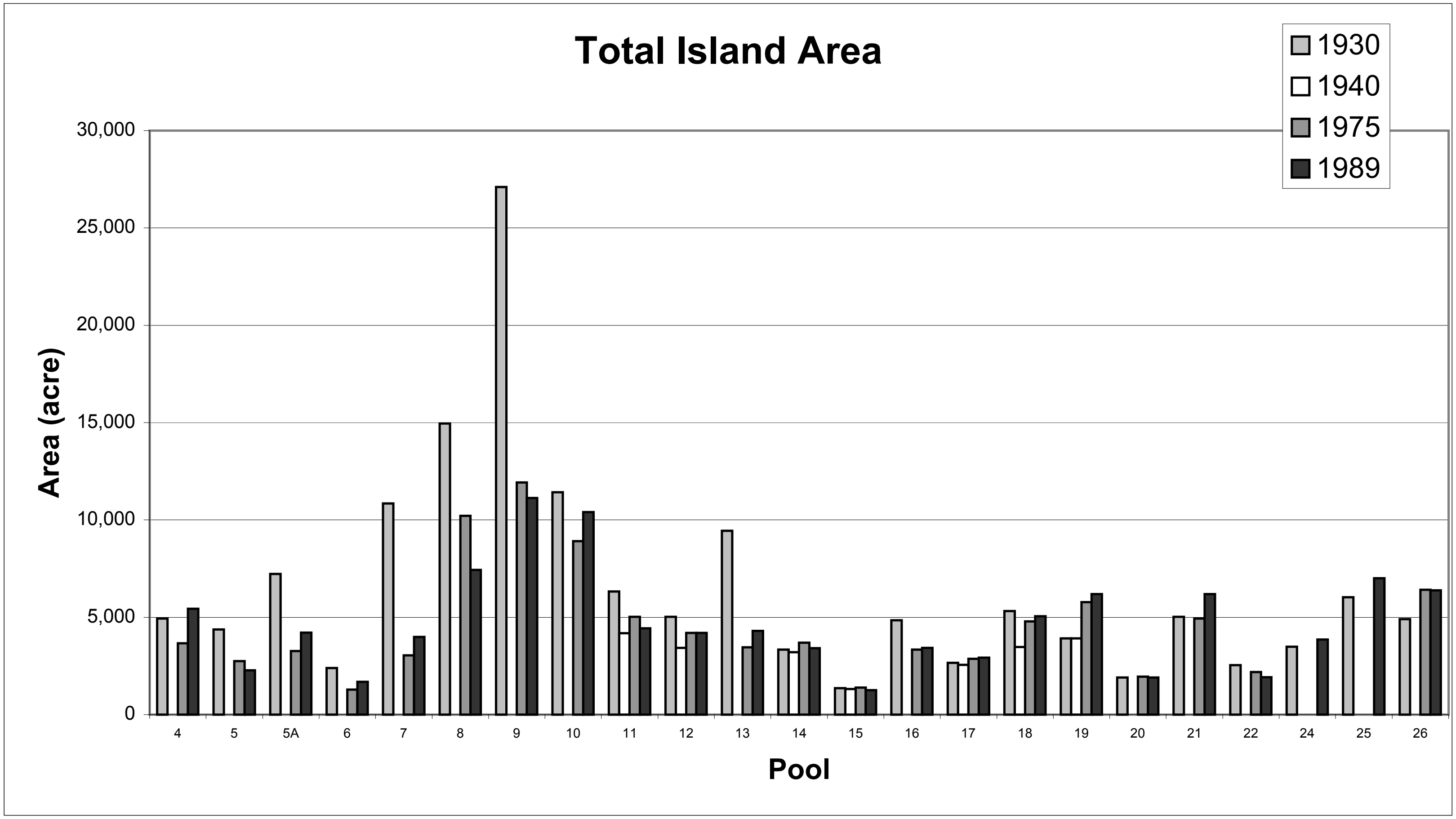


Figure 5-39: Area of islands, for every pool for the four time periods, measured from the plan form data. Missing columns represent data gaps in the coverage (the years in the legend represents timeframe, see Table 5-8 for actual years).

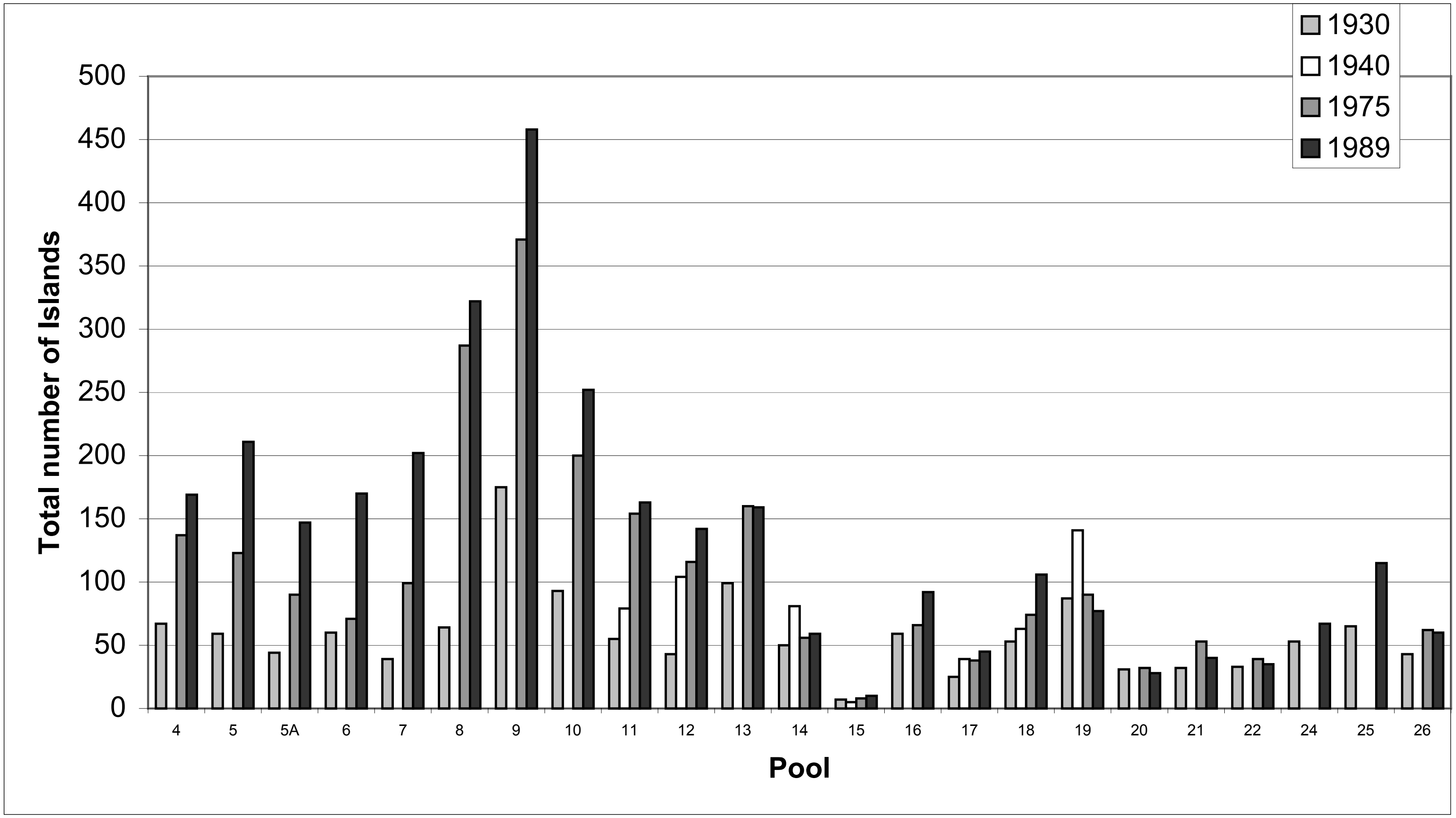


Figure 5-40: Number of islands, for every pool for the four time periods, measured from the plan form data. Missing columns represent data gaps in the coverage (the years in the legend represents timeframe, see Table 5-8 for actual years).

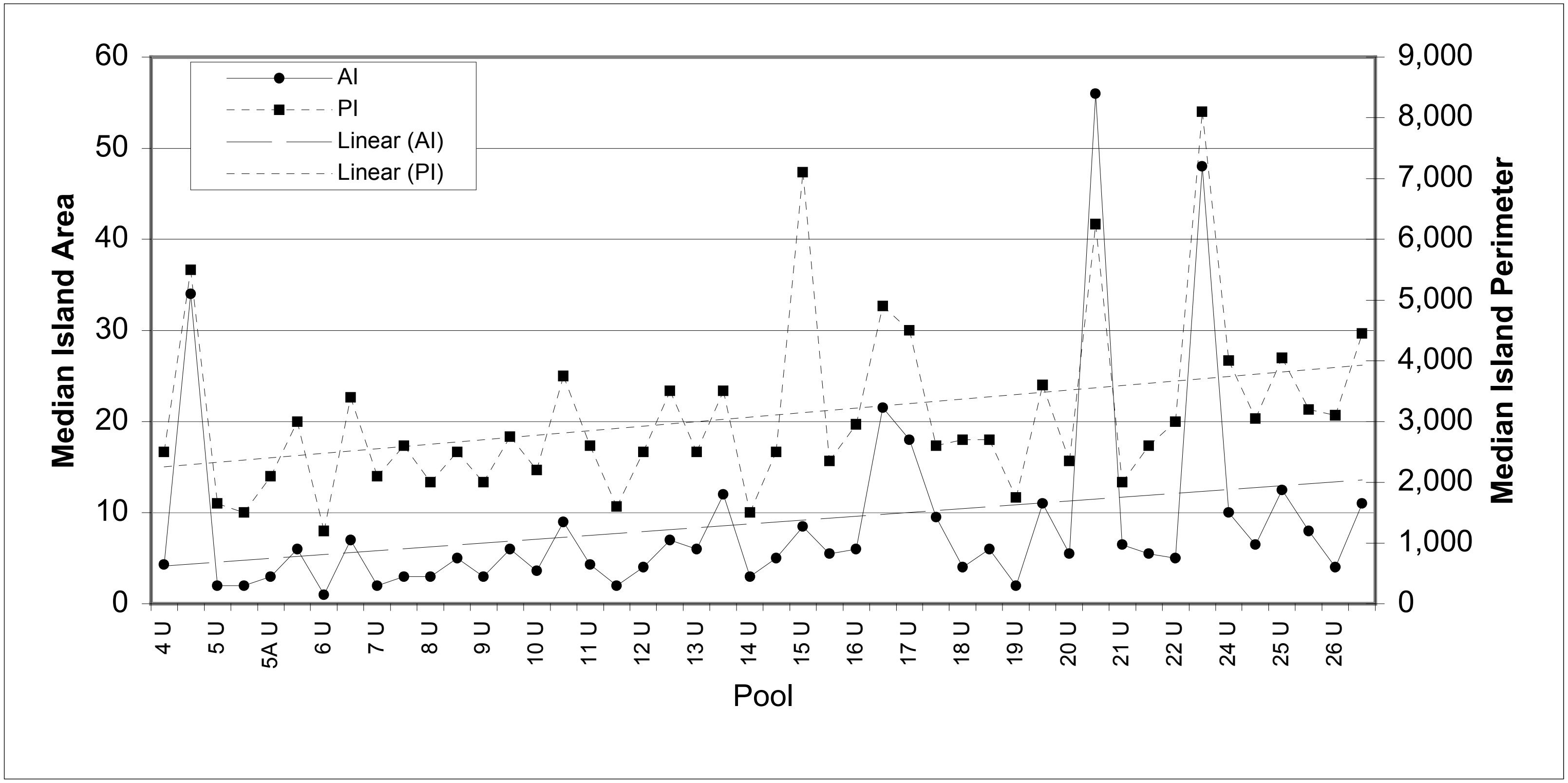


Figure 5-41: Median area and perimeter of islands for upper (U) and lower (L) pool. The two broken lines are trend lines through each data set.

In downstream pools, islands have in some cases been created by sedimentation between wing dams. Sedimentation may be due to both placement of dredge material or deposition caused by hydraulics of flow. In turn, secondary channels are created between the islands and uplands. Such islands are in many cases very elongated.

The Open River section of the UMR, Geomorphic Reaches 9 and 10 (River Miles 202 to 0), is characterized as a main channel with several secondary channels. In Figure 5-43 the area of aquatic classes for the Open River is presented. These areas were calculated using an aquatic areas GIS coverage developed by the USACE (WES, 1989). The total backwater area within the Open River segment of the UMR is small. Most of the existing contiguous and isolated backwater has been created by blocking secondary channels with wing dams. The diversity in aquatic areas for the Open River is therefore much lower than for upstream reaches.

Craig (Personal communication with M. Craig, 1998) has investigated historical changes in individual secondary channels along the Open River. As shown in Figure 5-42, plan form changes over the period of 1950 or 1952 to 1994 for five out of six secondary channels investigated show a substantial decrease in aquatic classes (open water). In most cases, the decrease in secondary channel area is more than 50 percent over the approximate 45-year period. Only one of the secondary channels investigated appears to be relatively stable.

Simons et al. (1974) identified bank lines for the Open River segment of the UMR from the confluence with Ohio (RM 0) to RM 170 for the years 1880 and 1968. The number of secondary channels for 1880 and 1968, shown on these plots, are 35 and 27, respectively. A total of 25 secondary channels could be identified from a 1989 Land Cover/Land Use GIS coverage (EMTC, 1998) for the Open River. Of the 25 secondary channels identified, 10 of them were seen to have been blocked by human actions. Including the blocked channels, the historic numbers of secondary channels imply that about 1 secondary channel is lost every ten years and the rate of change has been similar over the last 100 years.

In summary, the diversity of plan form features for the UMR decreases from upstream to downstream. The plan form statistics presented define historic plan form changes over approximately 600 river miles of the UMR, encompassing 23 navigation pools. Although each navigation pool has unique characteristics, it is possible to group the UMR pools into ten reaches that share similar geomorphic controls. The number of plan form features identified from historical data generally decreases in the downstream direction indicating a trend toward a simpler and less diverse system in a downstream direction. This trend is most evident in the Open River segment of the UMR (from Lock and Dam 26 downstream to the Ohio River confluence) where aquatic classes are primarily limited to the main channel and a few remaining secondary channels.

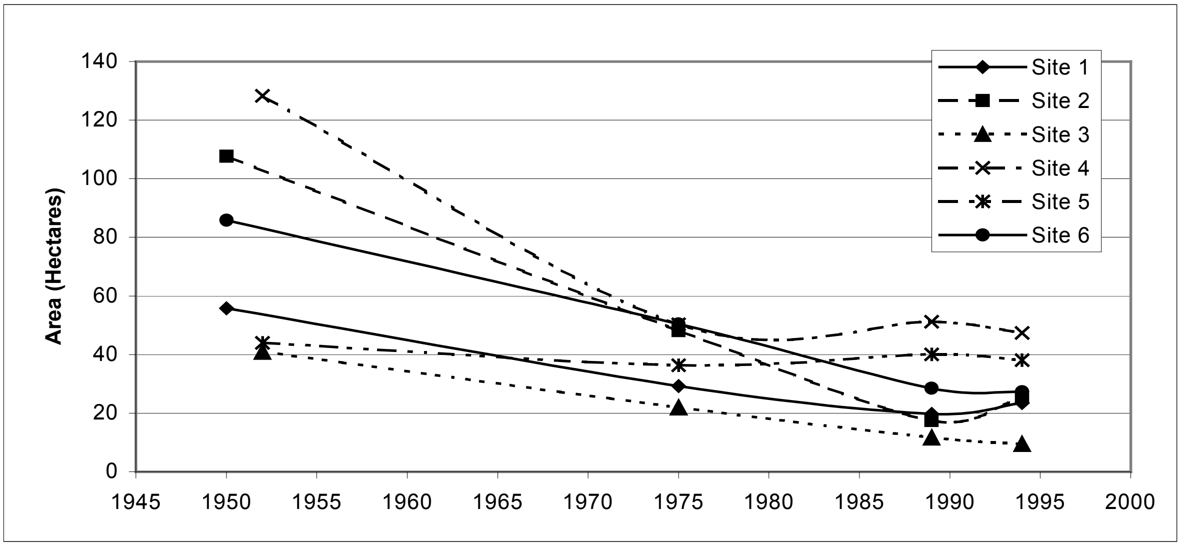


Figure 5-42: Area of aquatic classes for secondary channels in the Open River Reach. (Data source: Personal communications with Craig, 1998).

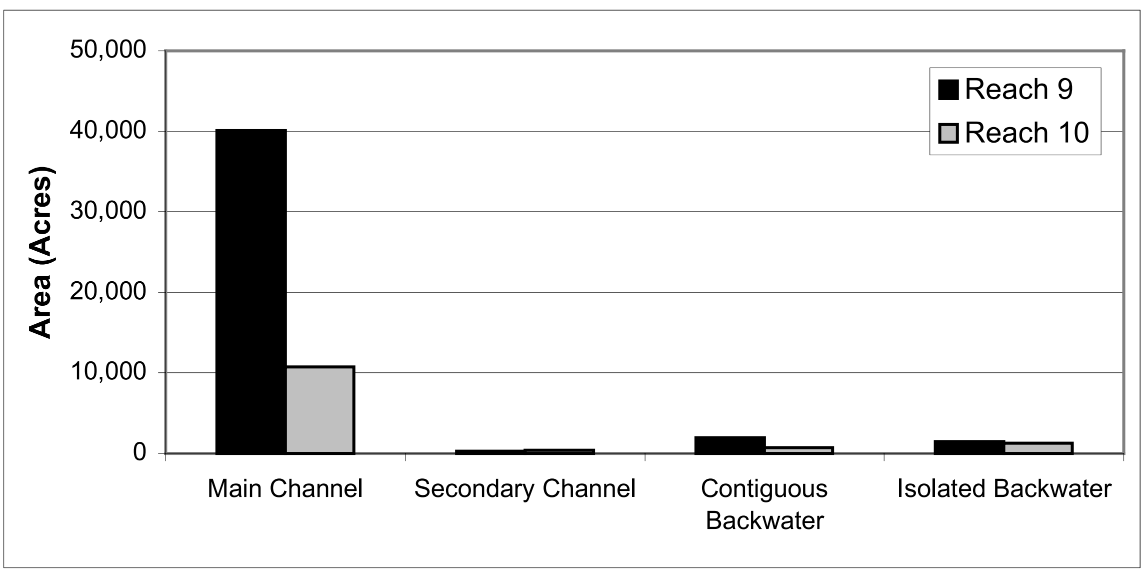


Figure 5-43: Area of aquatic classes for Geomorphic Reaches 9 and 10 (Open River). (Data source: WES GIS Aquatic Coverage).

5.5.3 Results for Illinois Waterway

5.5.3.1 Plan Form Data for Illinois Waterway

As listed in Table 5-8 plan form data for the Illinois River was only available for 1994. Consequently, only limited analysis and comparison of historic plan form conditions along the IWW could be conducted. The same aquatic classes were measured for the IWW 1994 data set as were for UMR plan form analysis described above.

5.5.3.2 Discussion

As discussed in Section 5.2.2, the IWW can be broken into two general geomorphic reaches based on the slope of the river.

Geomorphic Reach 1 involves the Starved Rock, Marseilles, and Dresden Pools. Upstream of Dresden the IWW runs more and less in a man-made channel. The IWW in Reach 1 is much steeper than the average slope for the UMR. As shown in Figure 5-44, impoundment effects in both the Dresden and Starved Rock Pools are evident as widening of the main channel. The aquatic classes measured for each pool are shown in Figure 5-45. As seen from the figure, the aquatic areas within the pools of the reach are mainly associated with the main channel. Only small areas of backwater were measured in each pool.

Geomorphic Reach 2 involves the three most downstream pools, Alton, LaGrange and Peoria Pools. These pools are about twice the length of the longest pool found along the UMR. The backwater from Lock and Dam 26 on the UMR controls conditions within the Alton Pool. The main channel for Reach 2 is relatively narrow and uniform. As seen in Figure 5-44 some slight increase in main channel width occurs upstream of the locks and dams associated with these pools. The only significant widening is seen in Lake Peoria.

As seen in Figure 5-45 the pools in Reach 2 have significant areas of backwater. In fact, the area of backwater is of the same order of magnitude as the area of main channel. In the case of LaGrange Pool, the area of backwater is about three times larger than the main channel area. In many instances, the backwater areas in Reach 2 are well-defined areas that are removed from the main channel. Numerous previous studies (e.g. Lee and Stall, 1976; Bellrose et al., 1983; Demissie and Bhowmik, 1986; Demissie et al., 1992) have documented that backwater areas in Reach 2 are rapidly filling with sediments. These studies have included various predictions that backwater areas in Reach 2 will be lost due to sedimentation in the near future.

In many respects, the IWW is significantly different from the UMR. A primary difference being the glacial history of the IWW basin, which has effectively defined the future of Geomorphic Reach 2 of the IWW as a sink for sediment. The gradient of the waterway, oversized nature of its river valley, and highly erodible loess soils predispose the IWW to an aggradational nature. The rate of sedimentation and loss of backwater areas along the IWW; however, are highly influenced by human activities in the basin. Therefore, the present conditions of IWW are not necessarily a predictor of the future conditions of the UMR. In the same manner, the fate of the backwaters along the IWW should not be used as a direct predictor for the fate of backwaters along the UMR.

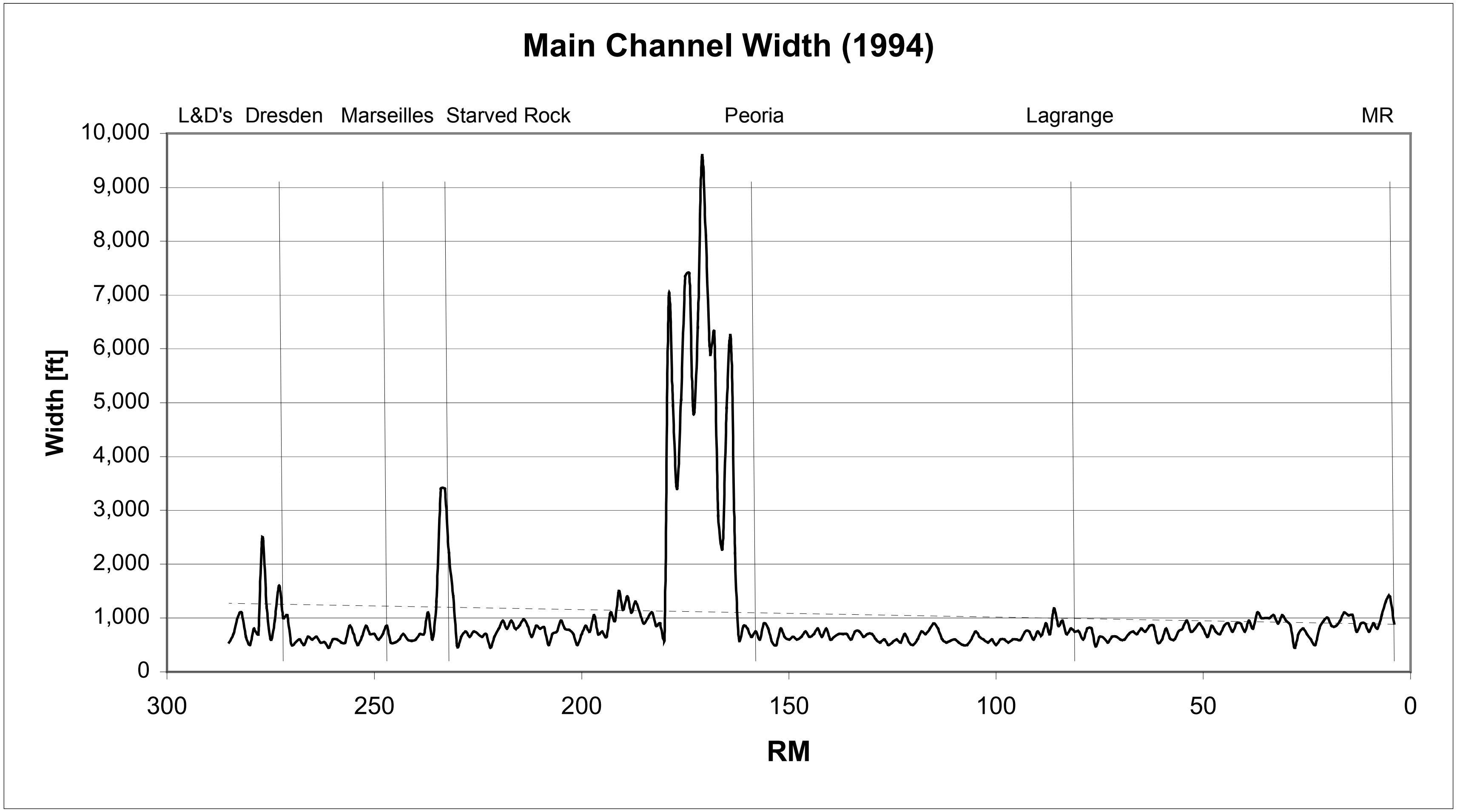


Figure 5-44: Main channel width of the IWW for every river mile as measured from plan form data for the year 1994. The vertical lines represent the location of locks and dams. The dashed line represents the linear trend for the width.

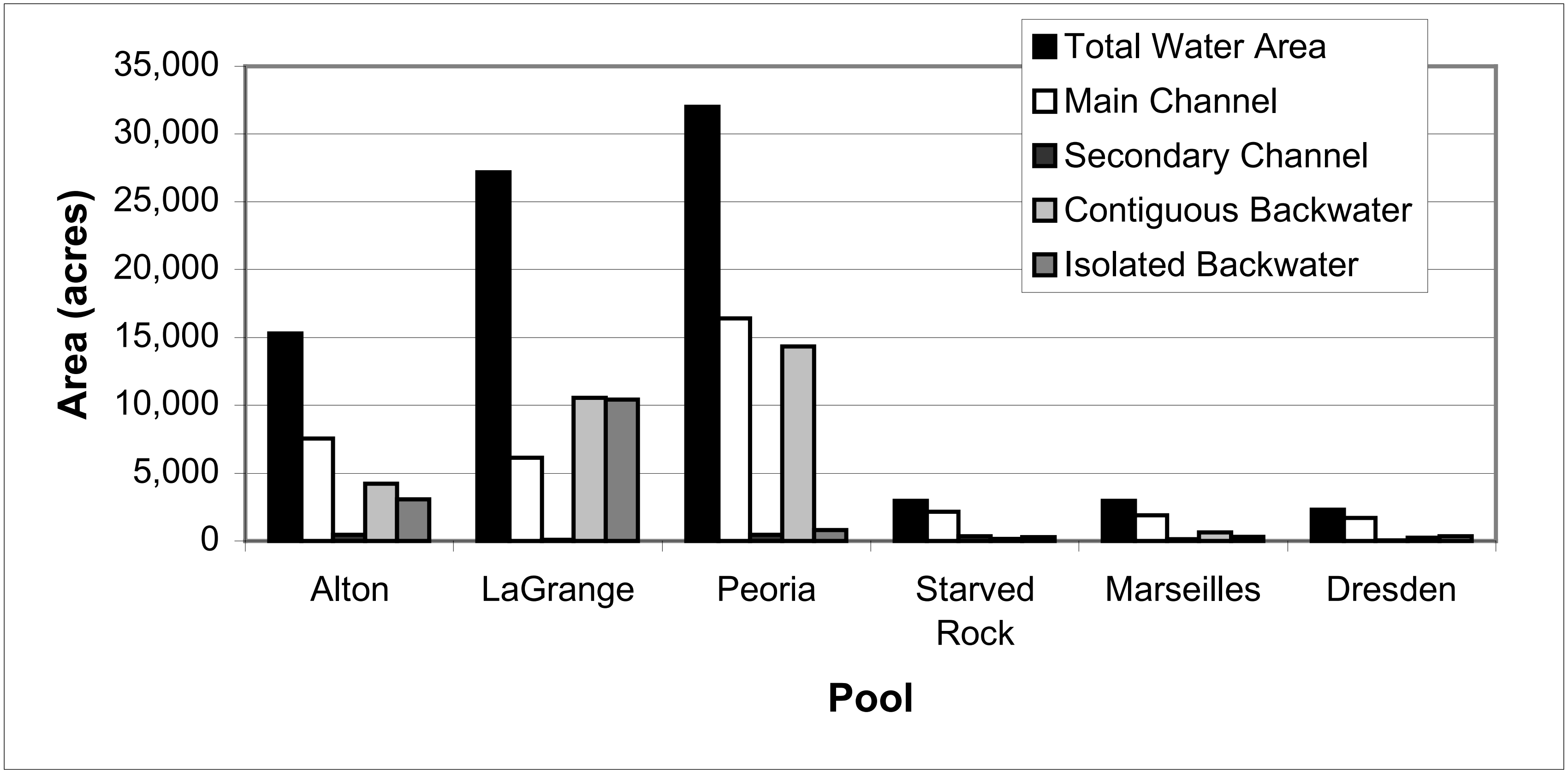


Figure 5-45: Area of aquatic classes, for every pool, measured from the plan form data.

5.5.4 Plan Form Overlays

Plan form overlays were developed for selected portions of the UMR system. In part, the purpose of the analysis was to provide a visual representation of the plan form changes presented in previous section. For the Open River and the IWW the plan form overlays demonstrate how little the mainstem has changed since impoundment.

5.5.4.1 Methods

The overlays were developed by matching different data types from different coordinate systems and projections to form the overlays. It is therefore not possible to obtain data on the differences between the two coverages by subtraction. The developed overlays are presented in Appendix G. The overlay data cover Pools 11, 14, 15, 19 the Open River and IWW.

5.5.4.2 Results

Upper Mississippi River

Overlays were developed for Pools 11, 14, 15, 19, and the Open River. These overlays serve as a visual representation of the plan form data presented in Section 5.5 and Appendix E. The following observations are made:

Pool 11: This overlay was created by overlaying the 1989 EMTC Land Cover / Land Use GIS Coverage on top of 1949 photography. Hence, the overlay spans 40 years. The overlay clearly shows tributary delta growth in the lower pool as well as island formation in the uppermost part of the lower pool. The loss of contiguous and isolated backwater is observed in the upper pool. Overall, the position of the main channel of the Mississippi River in Pool 11 has not changed significantly over the 40 years. The main channel of the Turkey River, in the upper pool, has changed its position significantly close to the Mississippi River mainstem. The Grant River delta growth observed in the overlay is depicted in a detailed photographic sequence in Section 5.5.5

Pool 14: This overlay was created by overlaying the 1989 EMTC Land Cover / Land Use GIS Coverage on top of 1940s photography. Hence, the overlay spans about 40 years. The loss of contiguous backwater is observed throughout the upper pool. In the lower portion of the pool, the UMR enters the Fulton to Rock Island gorge and consequently the lower portion of the pool is almost unchanged. The position of the main channel has not changed over the time period represented.

Pool 15: This overlay was created by overlaying the 1989 EMTC Land Cover / Land Use GIS Coverage on top of 1949 photography. Hence, the overlay spans 40 years. The UMR is located within the Fulton to Rock Island gorge. The observed change in water area is very small within the pool. It is expected that the pool will essentially remain the same for the next 50 years.

Pool 19: This overlay was created by overlaying the 1989 EMTC Land Cover / Land Use GIS Coverage on top of 1930 photography. Hence, the overlay spans 69 years. The overlay shows considerable decrease in backwater area in the upper pool with associate island merging and growth. The lower pool does not show significant change, excluding some tributary delta growth. Although the plan form comparison shows small changes in the lower pool, available bathymetry data show large under water deposition during this time period. The position of the main channel has not changed during the time period represented.

Open River: This overlay was created by overlaying mid-1980s era land/water boundary information (EMTC, 1998) on top of bank lines for 1968 identified by Simons et al. (1974). Hence, the overlay spans nearly 20 years. The main channel is almost unchanged for the whole Open River segment of the UMR for this period, in both width and location. However, it is emphasized that a georeferenced comparison was not possible for the data set. Significant adjustments were made to line up the coverages. The aquatic complexity of the UMR is low for the Open River reach. The main channel is relatively straight, which is probably due to the relatively high number of wing dams along the reach. The limited diversity in aquatic classes along the reach is associated with the remaining secondary channels. The 1968 bank line data, shown in the overlay, were used to estimate the rate of decrease of secondary channels as is discussed in Section 5.5.2.2.

Illinois Waterway

This overlay was created by overlaying mid-1980s era land/water boundaries (EMTC, 1998) on top of 1930s maps (Personal communications with C. Beckert, 1998). Hence, the overlay spans about 50 years. The main channel for the whole river, from the confluence with Mississippi River upstream to the Brandon Lock and Dam was found to be almost completely unchanged in plan form. The river is relatively straight and the main channel is very narrow and well defined. This is probably due to human activities along the river, including drainage districts, levees and navigation. Considerable backwater areas exist along the main channel. However, the backwater areas are considerably different from those noted along the Mississippi River. In most cases, the backwaters are associated with off-channel lakes. As is discussed in Section 5.2, IWW can be divided into two main geomorphic reaches: the lower reach consisting of Alton, LaGrange and Peoria Pool, which are extremely flat and long pools and the upper reach consisting of Starved Rock, Marseilles and Dresden Pools, which are steep and short pools. Upstream of Dresden the IWW is more or less a man-made channel.

For the most downstream pool, Alton Pool, the backwater areas are concentrated close to the confluence with Mississippi River. The backwater areas appear to be the result of backwater effects from the construction of Lock and Dam 26 on the UMR. Since the Alton Pool is extremely flat, backwater from the UMR does influence the pool.

Backwater areas exist along the entire LaGrange Pool, both isolated and contiguous. The overlay of historic plan forms indicates a considerable reduction in area for almost all of the backwaters. Many of the backwaters are believed to have artificially controlled water level. In some cases, the openings to and from the main channel are also controlled. It is therefore hard to distinguish backwater area changes due to man-made influences from changes due to natural processes.

Peoria Pool is different from the two downstream pools as it consists of two lakes, Upper and Lower Peoria Lakes. The main channel flows through the lakes and they are well connected to the main channel. The overlays show very little reduction in water area for the Upper and Lower Peoria Lakes. However, it is known from bathymetry data and sediment budget data (Demissie, 1992) that the lakes are filling with sediment and various authors (e.g. Lee and Stall, 1976; Bellrose et al., 1983; Demisssie and Bhowmik, 1986; Demissie et al. 1992) have predicted it will convert to an emergent floodplain land surface in the near future. It could therefore be expected that plan form data would show large changes over the next decades, as the very shallow water areas will be tipped over to emergent areas. The main channel is maintained by USACE dredging.

Starved Rock, Marseilles and Dresden Pools are much shorter and steeper than the three downstream pools. The river is almost exclusively contained in a narrow single threaded channel with very limited areas of backwater. The backwater areas were observed to have decreased somewhat.

Overall, the overlays for the Illinois Waterway show a river that has changed very little in plan form over the last 50 years. However, the backwater areas observed, have decreased in most cases. It is noted that the relatively small backwater area losses observed may be misleading. The majority of change in backwater areas is likely occurring as underwater sediment deposition and is not detected by the plan form analysis.

5.5.5 Examples of Geomorphic Processes

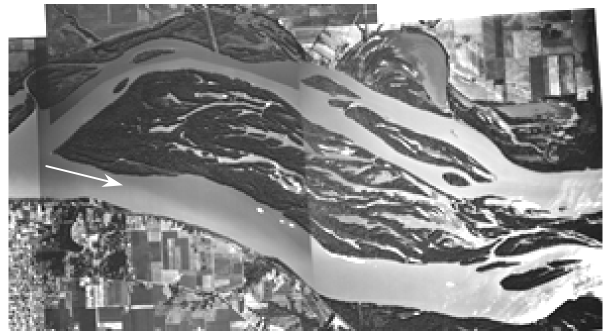
Geomorphic processes govern physical changes along the Upper Mississippi River. The examples of processes discussed in this section were identified to be acting along the UMR based on the analysis in this study. Concentrated areas of change associated with each of the nine characteristic processes were delineated on maps for each navigational pool along the UMR. The developed maps are presented in Appendix F. In the following subsections, typical examples are given for eight of the geomorphic processes. A good photographic example of island dissection was not available.

5.5.5.1 Loss of Contiguous Backwater and Filling of Isolated Backwater

Figure 5-46 shows a historical sequence of aerial photography for Burlington and Craigel Islands located between River Miles 397 and 403 in the upper portion of Pool 19. The 1941 photo shows that these islands were highly dissected by small backwater channels and lakes. By 1994, 54 years after the first photo was taken, the total area of these features has dramatically decreased. Many of the larger backwater areas have been reduced in size while many of the smaller backwater areas have disappeared altogether.

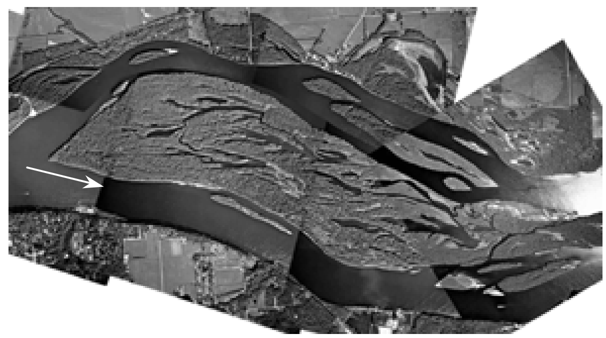
This reduction in backwater areas is likely due to the natural processes that occur during island evolution. During high water events in areas of flow expansion and velocity reduction, sediment is deposited and islands are sometimes formed.. As more sediment is deposited, vegetation takes hold and acts to hold the sediment in place as well as reduce flow velocities and trap more sediment during successive high flow events. Differential deposition of sediment as well as scour during high flow events can create channels and backwater areas within the island itself. The low-lying backwater areas formed by the river are then slowly filled in during successive high water events. These areas may then evolve over time from open contiguous backwaters, to isolated backwaters and ultimately to vegetated upland.

July 1941 (W.S.El. = 520.42 ft)



August 1957 (W.S.El. = 522.12 ft)

September 1984 (W.S.El. = 520.52 ft)



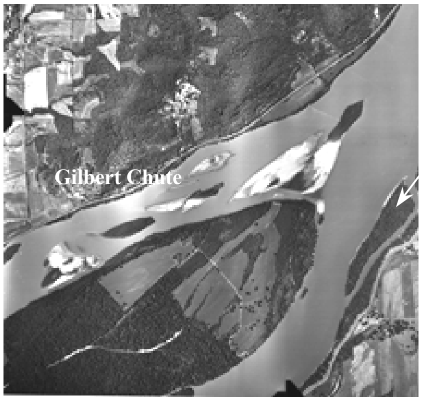
September 1994 (W.S.El. = 520.94 ft)

Figure 5-46: Photo sequence showing loss of contiguous backwater and filling of isolated backwater, Pool 19 (elevations are MSL).

5.5.5.2 Loss of Secondary Channel

Figure 5-47 shows a portion of Gilbert Chute from River Mile 295.5 to 299 in the upper portion of Pool 24. The 1956 photo shows a fairly wide secondary channel with a few small islands forming. By 1994, 39 years after this photo was taken, the secondary channel has experienced a large reduction in total water area, as smaller islands have grown together and reduced the complexity of the channel.

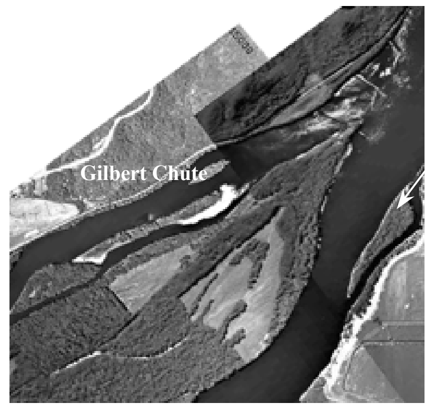
This reduction in channel area is likely due to the placement of a series of wing dams upstream and at the mouth of Gilbert Chute. The structures were built prior to the 1956 photos and acted to divert more flow away from the secondary channel. The wing dams have acted to reduce current velocities in the secondary channel, thus reducing the channels sediment transport capability. The 1956 and 1964 photos show a small lateral channel that cuts across the head of Gilbert Island. This channel may have helped keep the secondary channel clear of sediment deposits and slowed island growth. By 1984 this small lateral channel had disappeared and the smaller islands have grown together to form larger islands, thereby reducing the secondary channel size. Gilbert Chute will likely continue to decrease in size as long as the wing dams remain in place.



August 1956 (W.S.El. = 450.85 ft)

April 1964 (W.S.El. = 451.93 ft)

September 1984 (W.S.El. = 450.90 ft)

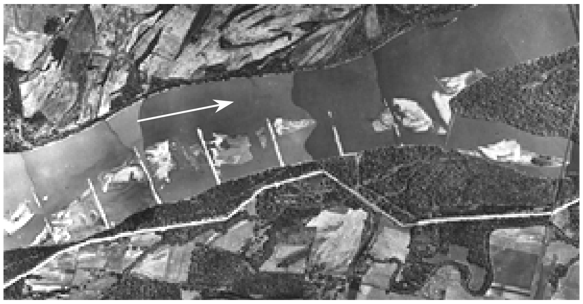


September 1994 (W.S.El. = 452.27 ft)

Figure 5-47: Photo sequence showing loss of secondary channel, Pool 24 (elevations are MSL)

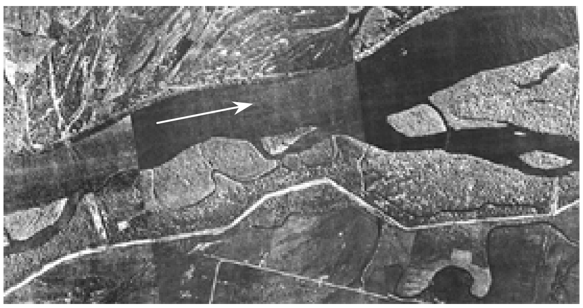
5.5.5.3 Filling between Wing Dams

Figure 5-48 shows a sequence of photos that depict sediment filling between wing dam structures from River Mile 428 to 431 in the upper portion of Pool 18. The 1930 photo was taken prior to the majority of locks and dams construction on the Upper Mississippi River. Lock and Dam 19 was in place, but is located 64 miles downstream. This photo shows the beginnings of sediment deposition between wing dam structures. By 1941, after Lock and Dam 18 was constructed, the majority of the area between the wing dams has filled with sediment. Small contiguous backwater channels have also formed from the current pattern created by these structures. By 1975 the deposited sediment has become covered with vegetation and appears to be fairly stable. Twenty years later the 1994 photo shows very little change, however there does appear to be some island growth in Blackhawk Chute, a secondary channel shown in the right side of the photo.

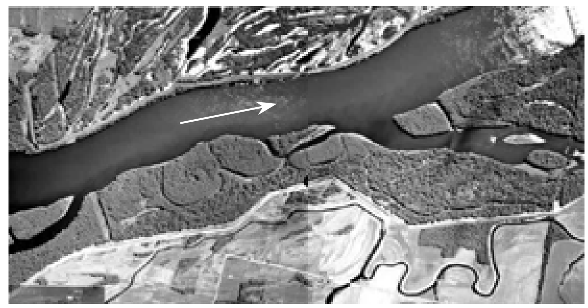


Summer 1930 (Pre-Dam)

July 1941 (W.S.El. = 528.02 ft)



September 1975 (W.S.El. = 528.00 ft)



September 1994 (W.S.El. = 527.96 ft)

Figure 5-48: Photo sequence showing filling between wing dams, Pool 18 (elevations are MSL).

Wing dams were constructed on the Upper Mississippi River as means to help maintain the navigation channel. By diverting flow into a narrower cross section of channel, velocities are increased, thereby increasing the channels sediment transport capability. Sediment that would otherwise be deposited in the channel is carried downstream or deposited between these structures. As a result of building these hydraulic control structures, areas of low velocity are formed between them. The low velocity areas act to trap the sediment until they become filled and the channel bank has migrated to a stable location near the stream side ends of these structures. The main channel is transformed from a shallow wide channel to a narrower and deeper channel, allowing easier navigation of the river.

The construction of the locks and dams on the Upper Mississippi River probably had only modest effects on the deposition of sediment between this set of wing dams. Dam construction may have acted to reduce channel velocities and therefore increase sediment deposition between the wing dams. Dam construction may also have acted to trap sediment and reduce the supply to this area, therefore reducing deposition. Most likely, the rate of deposition is controlled by the Iowa River, which enters the Mississippi River just 2.5 miles upstream of this location.

5.5.5.4 Wind-Wave Erosion of Islands

Figure 5-49 plots changes in area of islands from Figure 5-50 which shows a sequence of photos of wind-wave erosion of islands in lower portion of Pool 8, between River Mile 688 and Lock and Dam 8. The photo sequence starts right after impoundment. The impoundment flooded large areas, creating a large number of new islands as the high points of the natural topography peaked above the impoundment water level. The wind-wave erosion started right away, as many of the new islands were vulnerable to wind wave action due to their low heights above the pool and it is likely that the bottom bathymetry is simplifying. In fact, topographic surveys taken prior to inundation indicate that the elevation of many of the island areas shown in Figure 5-50 were actually below low pool elevations. As is shown in Figure 5-49 the area of islands has steadily decreased, though at different rates for different time periods. The erosion rate was highest for the first ten years and then slowed for the next 20 years and then picked up again. The change over the last ten years, from 1983 to 1994, has been almost zero. According to Hendrickson (Personal communications, 1998), Pool 8 is not in a dynamic equilibrium. The zero change in area of islands is due to pro-active rehabilitation program that reversed the trend in the lower pool. Furthermore, lower Pool 8 does not have the hydraulic energy to transport part of the upstream course sediment load. Consequently, dredging is performed at Brownsville and deltas are forming at the terminus of the sloughs in the middle reach of the pool.

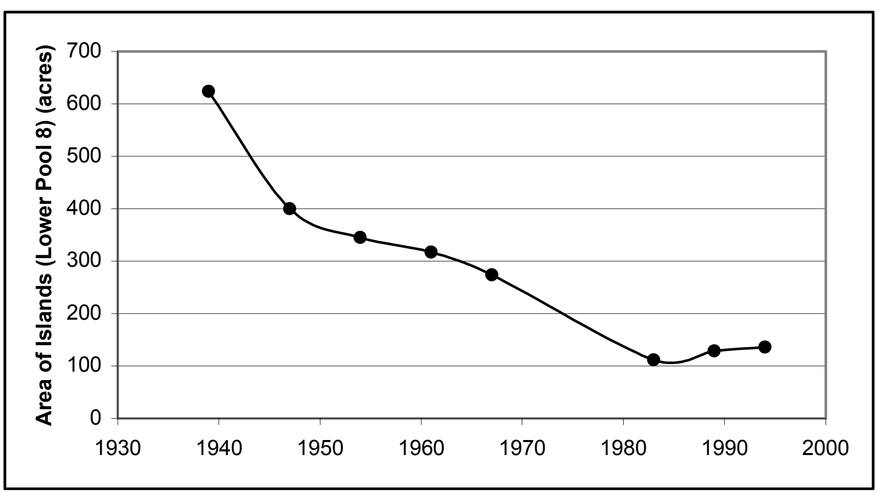


Figure 5-49: Area of islands for lower portion of Pool 8 shown in Figure 5-50.

Figure 5-50: The photo sequence shows island erosion in lower Pool 8. Dark gray areas are islands and light gray areas are water. (Source: Personal Communication with Theiling, 1998).

5.5.5.5 Tributary Delta Formation

The Grant River and Potosi Creek tributary deltas are located in Pool 11 at River Mile 593. Figure 5-51 shows the formation of these deltas for a 55-year period from 1940 to 1994. These deltas formed as a direct result of the impoundment of the Mississippi River by Lock and Dam 11 in 1937. Between 1964 and 1984 the two deltas had grown together to form one larger delta with an area of isolated backwater between them. Vegetation became established on the Grant River delta sometime between 1940 and 1949.

The greatest amount of delta growth occurred between the completion of Lock and Dam 11 in 1937 and 1984 with very little change occurring during the 10-year period from 1984 to 1994. This may be due to the decrease in the main channel width caused by the increase in delta size. Another factor contributing to the reduced rate of delta growth in recent decades is the dramatic reduction of upland soil erosion that has occurred in response to changing agricultural practices since the 1950s (Knox and Hudson, 1995; Argabright *et al*., 1996). This narrowing of the main channel acts to increase the main channel current velocities. The increased current has the ability to move the majority of the incoming sediment that would normally deposit at the mouth of the delta further downstream. As a result a reduction in the lateral growth rate of delta occurs while the delta continues to grow in the downstream direction.

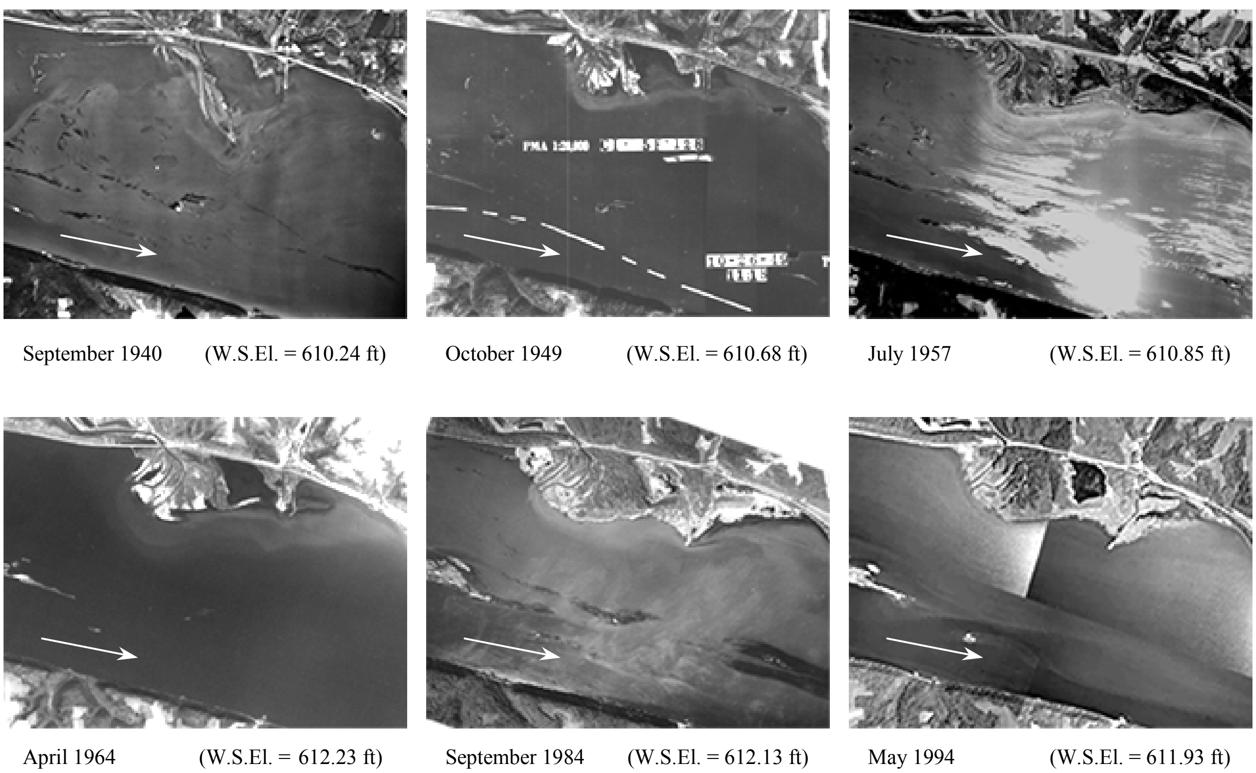
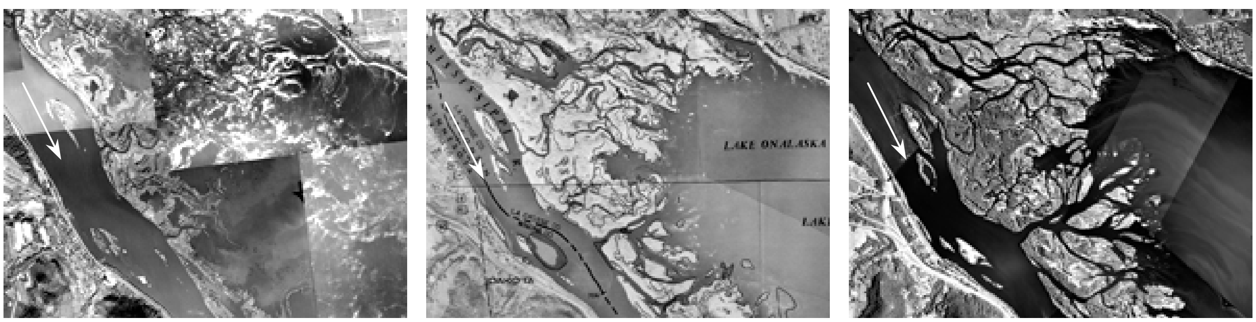


Figure 5-51: Photo sequence showing the formation of a tributary delta, Pool 11 (elevations are MSL).

5.5.5.6 Delta Formation

Figure 5-52 shows the formation of a delta into Lake Onalaska at River Mile 706.5 in the lower portion of Pool 7. The 1938 photo was taken approximately 1.5 years after the completion of Lock and Dam 7. This photo shows the beginnings of a delta forming from one of the small channels linking the Mississippi River with Lake Onalaska. By 1973 this channel has widened and lengthened as well as deposited large quantities of sediment into Lake Onalaska in the shape of a delta. By 1996, the small channel has become much wider and much longer and formed into multiple channels that interfinger throughout the entire delta. This delta has reduced the open water area in the upper portion of Lake Onalaska over the 60-year period after the completion of Lock and Dam 7.

This Delta and Lake Onalaska were both formed as a direct result of the backwater created by Lock and Dam 7. Lake Onalaska was converted from a low-lying marsh with small open water lakes into a very large shallow body of water. The feeder channels that exchanged water between the Mississippi River and this wetland area became much deeper due to the backwater created by the dam. This allowed for an increase in the ability of these channels to carry sediment. As more sediment was carried from the main channel of the Mississippi River through these channels into the open water area of Lake Onalaska, deltas began to grow and encroach into the expanded lake areas.



September 1938 (W.S.El. = unknown) 1973 (W.S.El. = unknown) August 1996 (W.S.El. = unknown)

Figure 5-52: Photo sequence showing the formation of a delta into Lake Onalaska, Pool 7 (elevations are MSL)

5.5.5.7 Island Formation

Figure 5-53 shows the formation of islands in the lower portion of Pool 12 from River Mile 559 to 564. The 1940 photo was taken approximately 2 years after the completion of Lock and Dam 12. The backwater from this dam has partially submerged the islands shown in this photo. By 1964, very little change has occurred above the surface of the water. The 1984 photo however, shows a noticeable increase in island surface area. The 1994 photo shows slight increases in the lengths of some of the islands.

The formation and growth of these islands is likely a response from the river to the submergence of existing islands by Lock and Dam 12. These submerged islands form a shallow water zone with greater roughness than the main channel. During high flow events sediment will tend to deposit in these areas helping to increase the size of the islands.

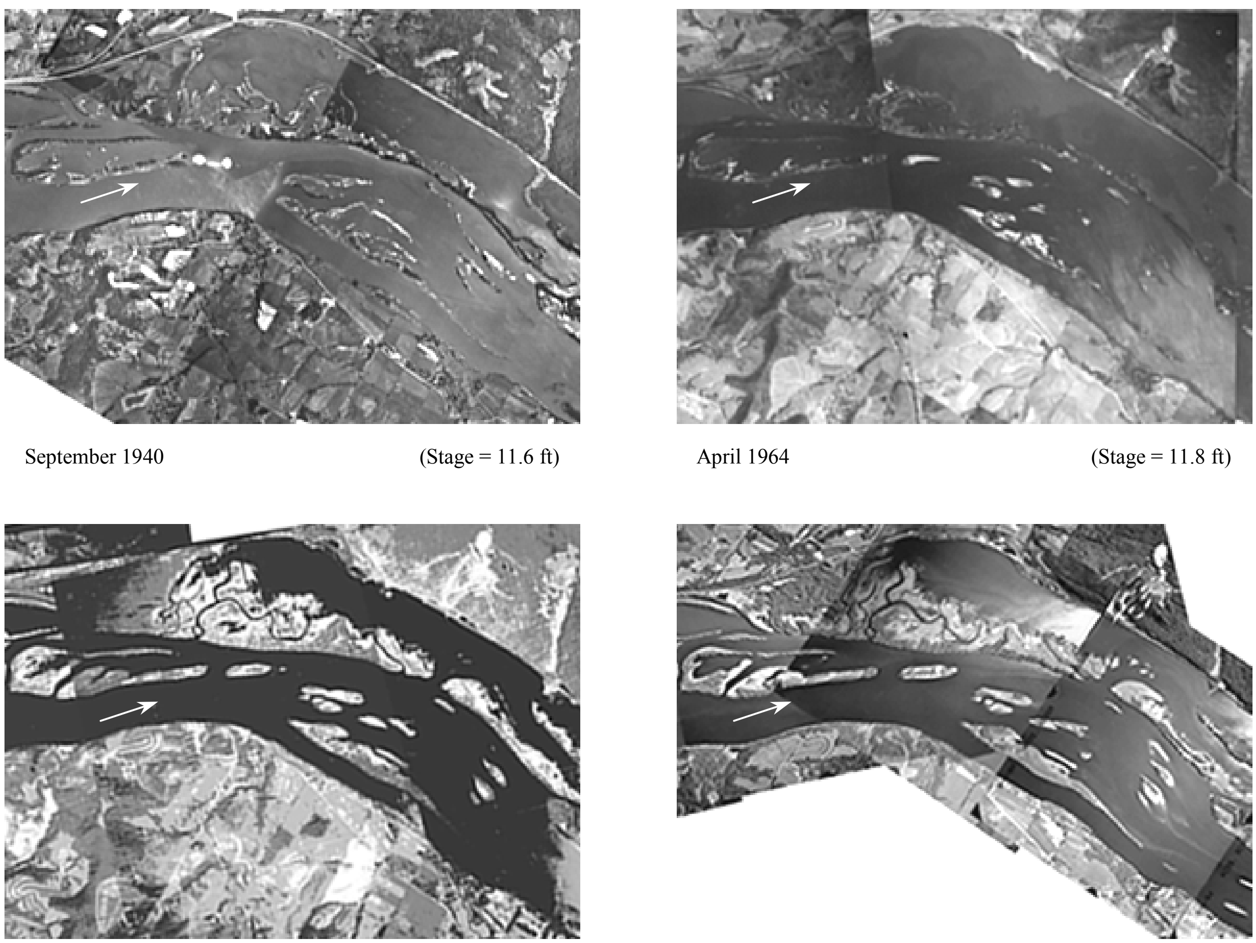


Figure 5-53: Photo sequence showing island formation in Pool 12 (stage reading taken at Lock and Dam 12)

5.6 CROSS SECTION ANALYSIS

An analysis of historic cross section data for the UMR was conducted. The goals of the analysis are to document changes in general channel geometry, identify trends in channel geometry change, and estimate volumes of sediment stored or eroded within the main channel of the UMR. Discussion of the methods and results of the analysis are presented in the following sections.

5.6.1 Methods

The cross section data is primarily from five sources: 1995 data, obtained from WES that includes cross sections at every whole river mile throughout the length of the UMR; data obtained from USACE Rock Island District were obtained from sedimentation surveys from various time periods; historical cross sections used in Nakato's (1981a) sediment budget; mid-1970s era cross sections from USACE St. Paul District UNET model and mid-1970s era cross sections obtained from St. Louis District. A total of nearly 2,000 cross sections were evaluated and processed. The coverage and extent of historical cross sections is most complete in the Rock Island District. In most cases, the historical cross section data extend from bank to bank but the 1995 WES cross section data are mostly contained in the main channel. The quality of the cross section data was in some cases not adequate for volume calculations. In some cases, the data were corrupted or cross sections for different time periods obviously did not line up. A judgement call was made for each cross section about its inclusion in the calculations. An example of typical cross section coverage is shown in Figure 5-54. Plots of all the cross sections are presented in Appendix H.

The volume of sediment stored in the main channel of the UMR was calculated using the cross sections presented in Appendix H. For each cross section location, area changes were calculated for each set of historic cross section using the trapezoidal rule. The calculations used the mean pool elevation as water surface elevation. The areas for different time frames were subtracted and multiplied by the distance between successive cross sections to determine volume changes.

5.6.2 Results

Plots of all historical cross section data are presented in Appendix H. The cross sectional plots show that the river can change significantly between time frames and stations along the river. Local conditions at each cross section influence the development of the cross sectional shape. These conditions include construction of wing dams which can lead to deposition behind the wing dam and degradation of the navigational channel; dredging and location of placement sites; the relative location of the cross section to bends; secondary channel size, and configuration and relative location in the pool.

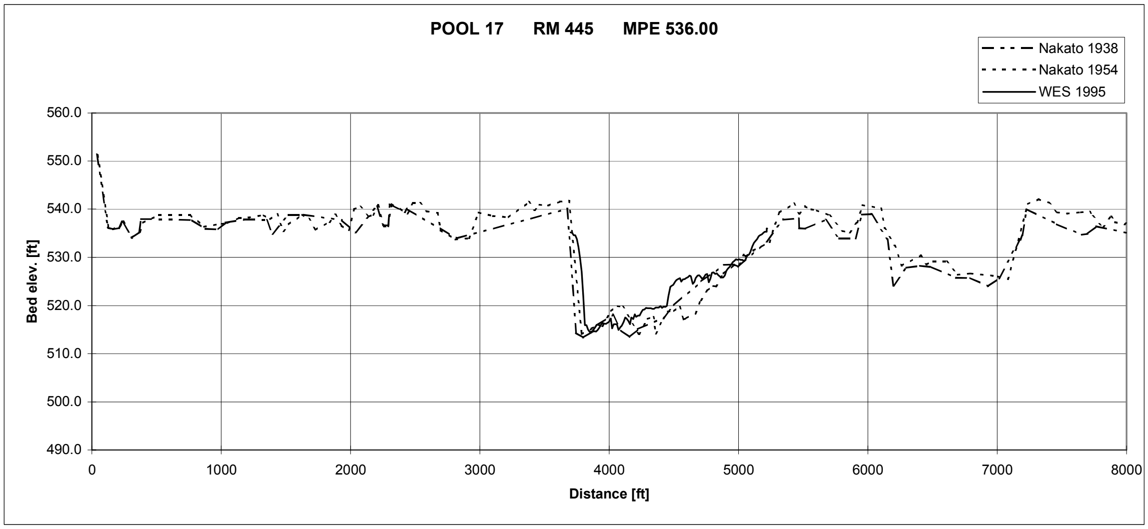


Figure 5-54: Typical plot of the cross section data. The WES 1995 data usually only extend across the main channel but the historical data usually extend from bank to bank. In this case the data source for the historical data is Nakato's sediment budget (Nakato, 1981).

The cross sections are used to calculate the main channel storage for different time periods. Period I generally consists of the period from immediately after impoundment (1940) to the mid-1950s. Period II generally represents the period from the mid-1950s to present (1995). The results from these calculations are used in Chapter 6 to develop the sediment budget. The cross sectional coverage in the Rock Island District and the St. Louis District is sufficient for calculating volume changes. The available cross section data for St. Paul are not sufficient for this purpose. In Table 5-10, the main channel storage estimates are listed for each pool. By dividing the volume of sediment determined to be stored in a pool, during a specific time period, by the area of the pool represented by the involved cross sections, the main channel accumulation rate is calculated. The main channel sediment accumulation rate for each pool is shown in Table 5-10. Figure 5-55 presents the variation in main channel sediment storage graphically. Figure 5-56 presents the main channel accumulation graphically.

As seen from Table 5-10 and Figure 5-56, lower Pool 19 was a large sink for sediment during Period I but experiences degradation during the second time period. Pool 19 is noted to be very different from the other UMR pools, mostly because of it large storage volume caused by the height of its dam. Pool 11 has experienced similar accumulation for both time periods whereas other UMR pools listed in the table experienced large drop in sediment accumulation from time period I to time period II and in many cases the main channel is degrading. It is noted that an extreme flood event occurred in 1993. The specific influence of the flood on the channel cross section geometry is unknown. It is possible that the flood may have had significant impacts to the channel geometry.

The main channel in Pools 14, 20, and 22 has degraded more than one cm/year during the second time period. This is equal to 1.5-2 ft degradation over approximately the last 50 years. Overall, the main channel experienced deposition, with Pool 19 as the major sink, for the first time period and degradation for the second time period. It is emphasized that these calculations are restricted to the main channel due to the limitations of the 1995 cross section data. Deposition in backwater areas is discussed in Chapter 6.

A thalweg profile developed from the 1995 cross sectional data for the UMR is presented in Figure 5-57. The thalweg slope for each reach is shown on the figure, calculated as the best fit line through the thalweg data points. Reach 2 only encompasses Pool 4, which contains Lake Pepin and the Chippewa River delta. The thalweg plot clearly shows the effect of the Chippewa River delta in Pool 4 as a large dip in the profile immediately upstream of the delta at the downstream end of the lake. Reach 3 is relatively steep, as the Chippewa delta controls the upstream end of the reach. The upper portion of the reach is steeper than the lower portion as the influence of the Chippewa alluvial fan decreases going downstream. The spacing of the locks and dams in the reach reflect this affect as the spacing is more dense in the upstream part of the reach. Reach 4 is significantly flatter than Reach 3. This is probably due to the geology as the downstream end of the reach is controlled by erosion resistant bedrock. In many cases, the thalweg has scoured considerably immediately downstream of locks and dams; this is especially true in Reaches 3 and 4. The Fulton to Rock Island Rock Gorge is located at the upstream end of Reach 5 and the Fort Madison to Keokuk Rock Gorge is located at the downstream end. Relocation of the Mississippi River during former glaciations of the

Table 5-10: Main channel storage and accumulation rates for the main channel for Rock Island District and St. Louis District and their associated time periods.

	Period I	Period II	Period I	Period II	Sum	Period I	Period II
Pool			Main channel storage (tons/year)	Main channel storage (tons/year)	Main channel storage (ton/year)	Main channel accumulation (cm/yr)	Main channel accumulation (cm/yr)
11	'38 - '51	'51 - '95	695,857	655,679	1,351,536	1.80	1.84
12		'39 - '95		-214,385	-214,385		-0.71
13		'45 - '97		149,698	149,698		0.48
14	'38 - '44	'44 - '95	176,295	-428,872	-252,577	0.65	-1.31
15	'47 - '52	'52 - '95	366,415	-15,983	350,432	1.93	-0.10
16	'38 - '49	'49 - '95	793,750	-89,124	704,626	2.00	-0.22
17	'38 - '54	'54 - '95	303,607	-135,717	167,890	1.33	-0.58
18		'38 - '95		-199,241	-199,241		-0.50
19U	'38 - '46	'46 - '95	25,904	294,678	320,582	0.08	1.05
19L	'38 - '46	'46 - '95	4,996,751	-351,616	4,645,135	6.22	-0.31
20	'37 - '50	'50 - '95	-2,511	-434,012	-436,523	-0.01	-1.14
21	'38 - '53	'53 - '95	561,113	-176,589	384,524	1.89	-0.59
22	'38 - '54	'54 - '95	846,106	-473,325	372,781	2.08	-1.19
24		'77 - '95		-1,070,804	-1,070,804		-2.90
25		'77 - '95		1,587,598	1,587,598		3.40
26		'71 - '95		90,409	90,409		0.14

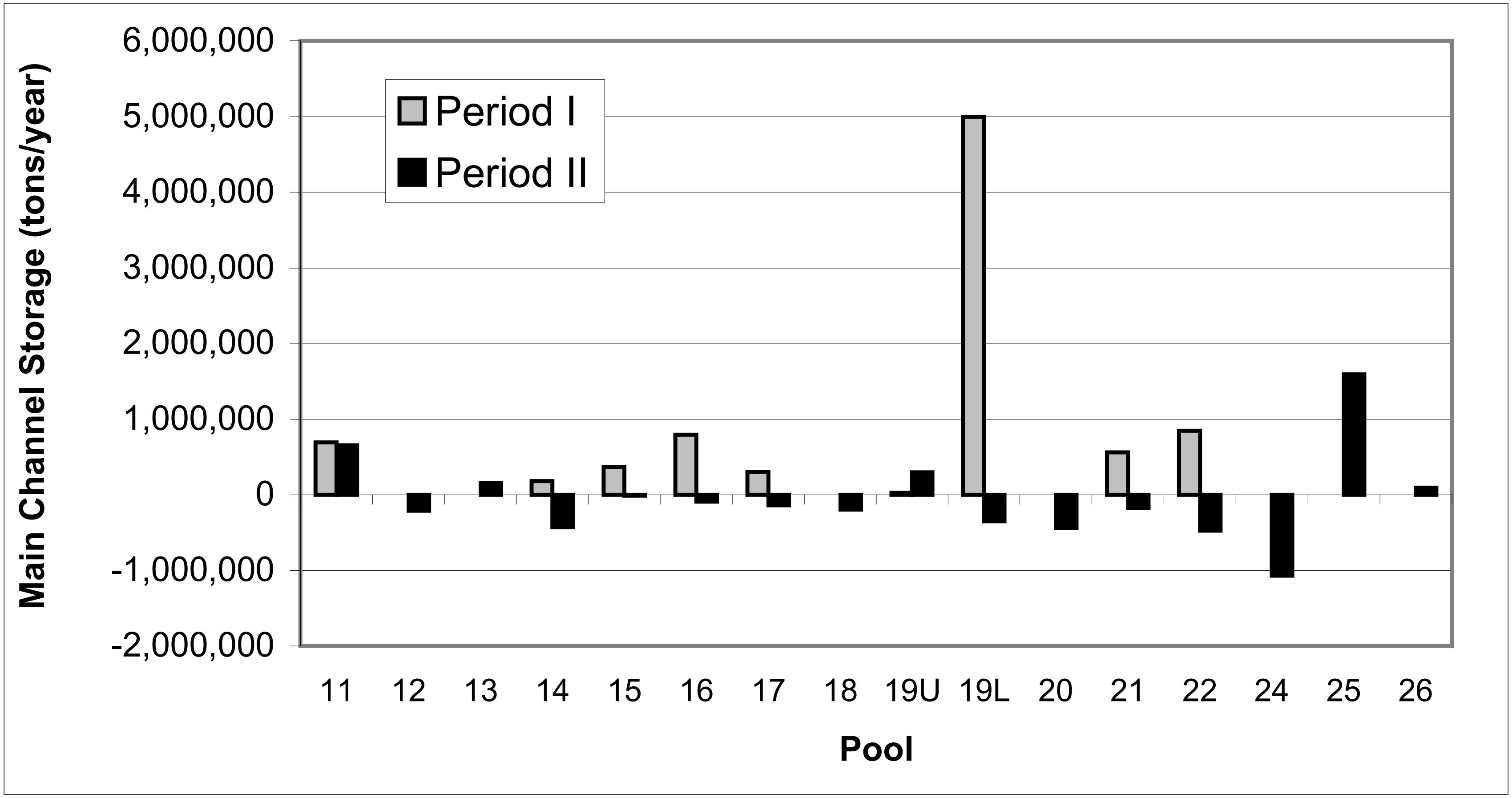


Figure 5-55: Main channel storage for by pool in Rock Island District for the available time periods. The time periods are defined in Table 5-10.

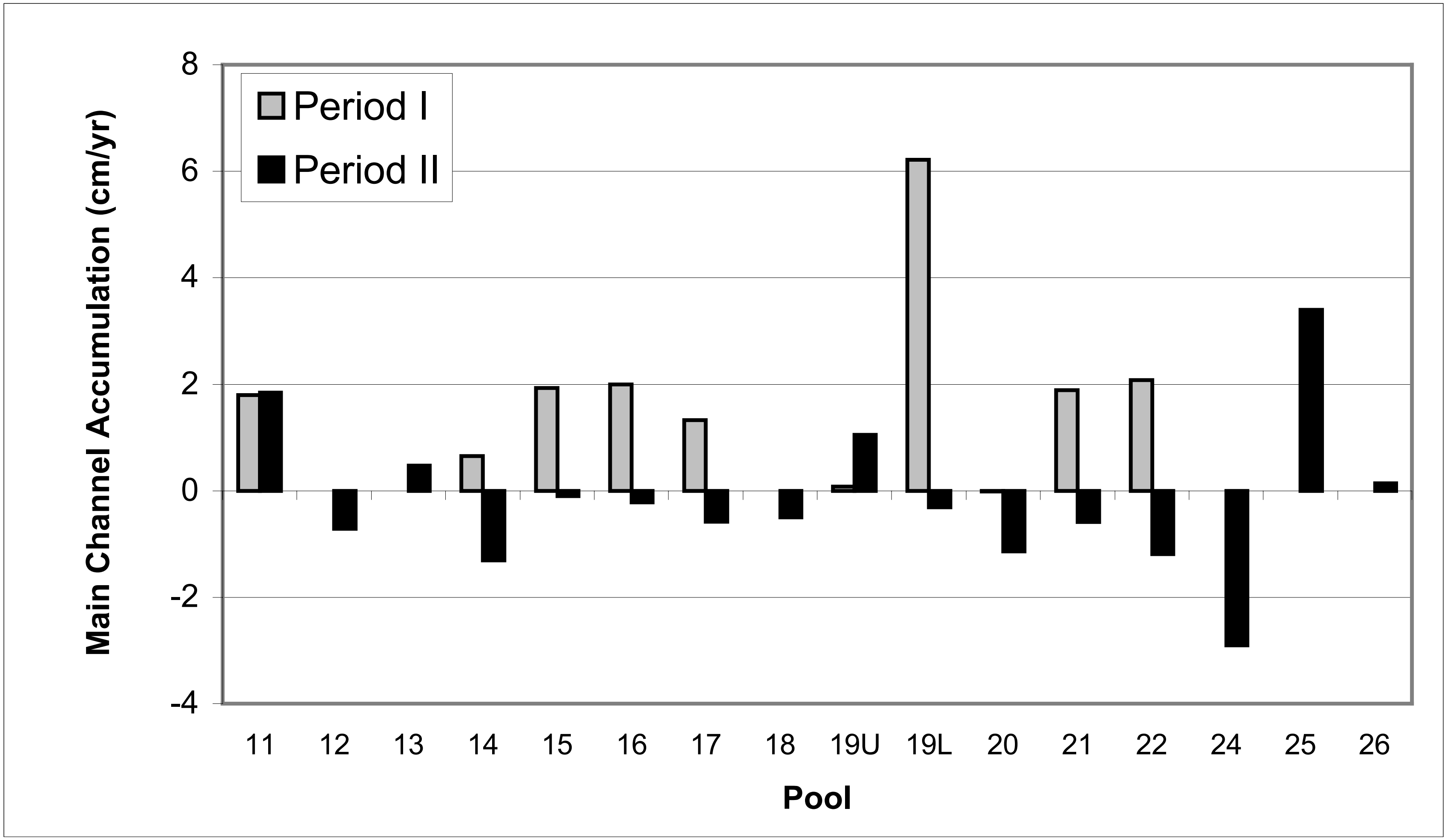


Figure 5-56: Accumulation rates for the main channel in Rock Island District for available time periods. The time periods are defined in Table 5-10.

region surrounding Reaches 5 and 6 resulted in incision of the Mississippi River through the narrow bedrock gorges and accounts for the high variability in the lengths of pools in Reaches 5 and 6. The anomalously steep bedrock channel in Pool 15 explains the short length of that pool. Farther downstream, the exceptionally long Pool 19 and the great drop in elevation of the water surface at Lock and Dam 19, reflects the early development of that structure for hydroelectric power generation and the associated need for a large hydraulic head. Reach 7 is relatively steep and the slope is uniform through the reach, consequently the spacing of the locks and dams along its length is also uniform. Reach 8 is almost concave in shape due to the influence of the alluvial fans of the Illinois and Missouri Rivers. This significant flattening of the profile results in considerable dredging requirements upstream of the confluence with Illinois River.

In Figure 5-58 the 1930 thalweg profile from the Brown Maps (Brown Survey, 1932) is plotted with the thalweg profile obtained from the 1995 WES survey (Figure 5-57). Figure 5-58 also shows the low water profile from the Brown survey as well as the mean flat pool elevations defined by WES. It should be noted that the flat pool elevation is not the same as a water surface profile. The water surface at the upstream end of each pool will generally be higher than the flat pool elevation. The comparison between the two thalweg profiles show that, on this scale, the changes in slope are small. It is also seen that the profile is influenced by geomorphic controls, such as the Chippewa River in Pool 4, the alluvial fan of the Wisconsin River, the bedrock in Pool 15, and the alluvial fans of the Illinois River and Missouri River. The geomorphic form of the river has dictated to a great extent the location of the Locks and Dams. On a smaller scale, degradation is generally observed downstream of the dams. Comparison of the Brown survey low water surface profile and the 1995 flat pool elevations shows that the low water profile was considerably affected by the installations of the locks and dams. The dams have significantly changed the energy gradient along the river. The energy gradient is much flatter within the pools and much steeper at the locks and dams. The altered energy gradient influences sediment transport and the evolution of geomorphic conditions along the river.

5.6.2.1 Backwater Sediment Accumulation Analysis For Pool 11

In only one location, lower Pool 11, is a comparison of historical cross section data for backwater areas possible. Table 5-11 shows a comparison of sediment deposition for off-main channel areas between River Miles 584 and 597. The area involved in the calculations is about 10 mi^2, which is of significant size. The calculated accumulation rate for the first time period, 1938-1951, shows an accumulation of 1.56 cm/year. For the second time period, 1951-1995, the accumulation rate was determined to be 0.34 cm/year. These results indicate that a dramatic decrease has occurred in the accumulation of sediment between the decades following the installation of the locks and dams to present. The decrease in accumulation rates is more than four-fold. The location of the cross sections analyzed are in the lower portion of the pool (as defined in Section 5.5) and therefore influenced by wind waves. Other researchers, such as McHenry et. al. (1984), Knox and Faulkner (1994), Rogala and Boma (1996) and GREAT-I (1980), have reported similar decreases in the sediment accumulation rates for backwater areas along the UMR.

It is noted that the main channel in the lower portion of Pool 11, during the second time period, continues to accumulate large amounts of sediment. This is probably due to the bed load supply from the upstream Wisconsin and Turkey Rivers and from the high magnitude contributions of suspended load sediment from several upstream and adjacent tributaries that drain this hilly agricultural region of thick, highly erodible loess deposits. The main channel in Pool 11 is still relatively deep in the lower pool so dredging has not resulted from the accumulation. It is reasonable to assume that future dredging requirements in lower Pool 11 will increase over the next decades. It is also possible that as the main channel narrows and shallows it will become more efficient in passing sediment to downstream pools. Hence, dredging requirement in Pools 12 and 13 could also increase.

In several of the UMR pools, the variability of the bottom topography has decreased significantly in areas upstream of the locks and dams. These areas, in many cases, were created as a result of the installation of the locks and dams. An example of this phenomenon is shown in Figure 5-59 for Pool 11. This simplification of bottom topography occurs most significantly in pools with large open backwaters, away from the main channel. The example shown in Figure 5-59 shows simplification of the topography away from the main channel which has the highest velocities and therefore the largest sediment carrying capacity. The in-filling of the cross section is not uniform, as there seems to be 2 to 3 secondary flow pathways in the right overbank. The flow paths are probably secondary channels that were flooded by the impoundment caused by the locks and dams. The sedimentation occurring in areas away from the main flow paths, smooth the bottom topography. Silt or finer material diffuses outward from the main flow paths, settling in more quiescent flow condition. This sediment is probably redistributed in shallow overbank areas by wave energy (from wind and/or boats). Ultimately, the sediment settles out in its lowest energy state, filling up the low spots, thereby simplifying the bottom topography.

Table 5-11: Historic Sediment accumulation for backwater areas in lower Pool 11 for two time periods (Based on cross section analysis).

Backwater Accumulation for River Miles 584 - 597					
Period	'38 – '51		Period	'51 - '95	
Area	10.421	mi^2	Area	10.435	mi^2
Accumulation	714,356	tons/year	Accumulation	156,222	tons/year
	0.05	ft/year		0.01	ft/year
	1.6	cm/year		0.3	cm/year

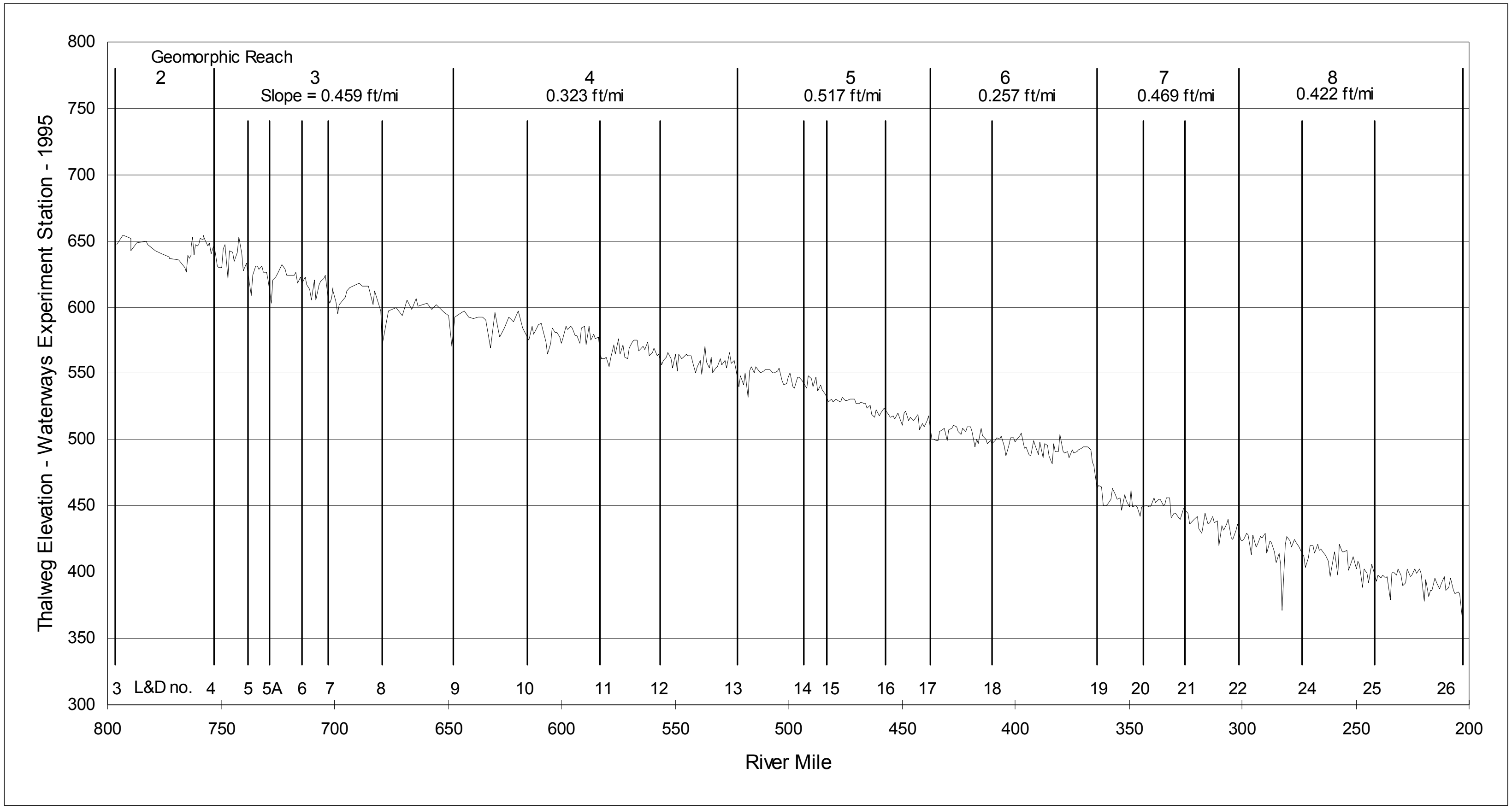


Figure 5-57: Thalweg elevation profile for the Upper Mississippi river for Pools 4-26. The thalweg elevation was obtained from the WES 1995 cross section data. The slope for each reach is the slope of a trend line through the thalweg elevations for each reach.

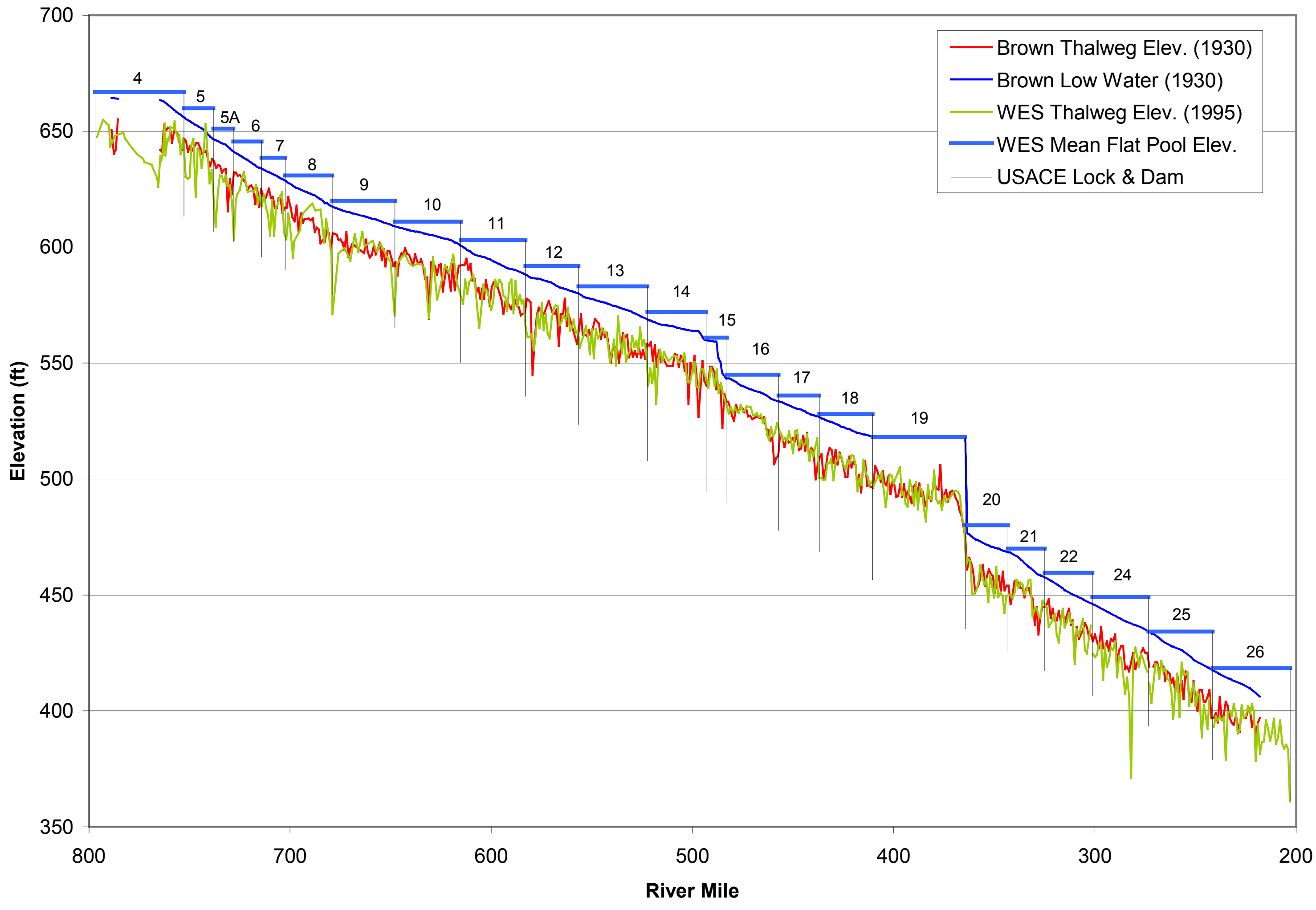


Figure 5-58: Comparison of the 1930 thalweg, from the Brown maps, to the 1995 thalweg surveyed by WES.

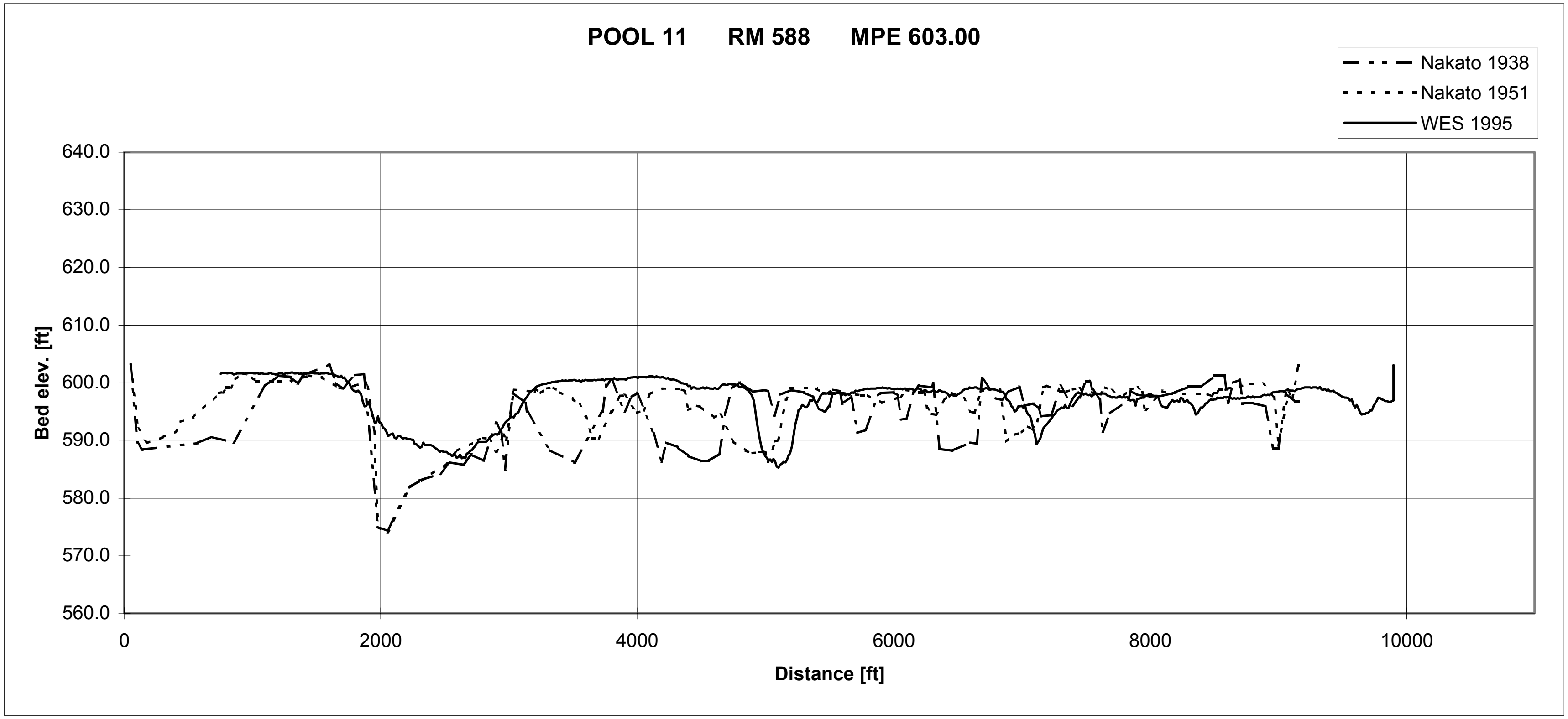


Figure 5-59: Example of the reduced under-water topographic variability.

6 SEDIMENT BUDGET

A sediment budget was developed to quantify sediment transport between successive navigation pools in the UMR locks and dams system. This work builds upon a similar previous effort by Nakato (1981a). The sediment budget defines historic change in the sediment transport characteristics of the UMR during the post-locks and dams impoundment era and recent sediment accumulation rates in the backwater[1] areas of navigation pools. In this chapter, the term backwater areas refers to off main channel areas, that is, areas that are not main channel areas as defined in Section 5.5. Information from the sediment budget can be used to improve existing operation and maintenance procedures, understand the physical and ecological impacts of the system, and formulate viable habitat restoration strategies. Limited cross section data was available for the St. Paul District and therefore the sediment budget is started in Pool 10. In the following sections, the methods and results of the sediment budget analysis are described.

6.1 METHODS

For each analysis reach, a budget of the sources and sinks for sediment was established to calculate the sediment output from the reach. The analysis reaches were defined as either a whole navigation pool or the portion of a pool bounded by a sediment measurement station. The sediment budget analysis involves a 415 mile long reach of the UMR (Pools 11 through 26). A total of 19 reaches were defined for the analysis. The limits of the sediment budget analysis were based on the availability of data. The data used in the sediment budget has been discussed in previous sections: tributary sediment data in Section 5.3; dredging data in Section 5.4.4; cross section data in Section 5.6; plan form data in Section 5.5 and long term sediment transport trends in Section 5.3.3.

The sediment budget is presented in two different versions for different purposes. First, in Section 6.2.1, the sediment budget is presented for two time periods in order to analyze historic changes that have occurred in main channel sediment storage, dredging, and tributary sediment load. Time Period I is from immediately post-dam to mid-1950s and Time Period II is approximately from mid-1950s to 1995. Dredging and main channel sediment storage records are available for both these time periods but tributary and main channel sediment loads are not available for Time Period I. In this version, the sediment budget is not adjusted at sediment measurements stations on the mainstem as the data are not available for Time Period I.

Second, in Section 6.2.2, the sediment budget is presented for Time Period II only. In this version, the budget is adjusted at each sediment measurement station as shown in Table 6-4. This version of the sediment budget should be used as an estimate of the present sediment transport condition for the UMR as the data used are the most recent. The sediment budget estimates the sediment load into each pool, the change in storage of sediment within each pool (Section 5.6), and the sediment outflow from each pool. At

[1] In discussions related to the sediment budget, backwater areas refer to off-main channel areas.

each mainstem sediment measurement station, the sediment load is adjusted to equal the sediment load that was measured at that station. The difference between the sediment load calculated by the sediment budget and the measured sediment load at the station provides an estimate of sediment transport into backwater areas between sediment measurements stations. Five mainstem sediment measurements stations with adequate long-term records were used in the analysis. Hence, the sediment budget represents four independent sediment budgets, one budget between every two adjacent sediment measurement stations.

Development of the sediment budget required quantification of the average annual sediment load transported along the Mississippi River and supplied from its tributaries, the storage of sediment within the main channel, and the average annual amount of dredging within each analysis reach. The sediment budget was calculated for the main channel (see definition of the main channel in Section 5.5) and the backwater sediment accumulation rate was calculated from the budget. As is explained in Section 6.1.2, whole channel cross section coverage was limited. A conceptual representation of the sediment budget is shown in Figure 6-1. The sediment budget for analysis reach *i* can be expressed as follows:

$$Qs^{i} - Qs^{i-1} = \sum_{j=1}^{n} qs_{j}^{i} + Qs_{bank}^{i} - Qs_{dre}^{i} - Qs_{sto}^{i} - Qs_{bw}^{i} \qquad \textbf{Equation 6-1}$$

where,

Qs^{i} = Total sediment discharge out of the *i*-th reach (tons/yr),

Qs^{i-1} = Total sediment discharge into the *i*-th reach (tons/yr),

qs_{j}^{i} = Total sediment discharge from the *j*-th tributary of the reach (tons/yr),

Qs_{bank}^{i} = Total sediment discharge from bank erosion in the reach (tons/yr),

Qs_{dre}^{i} = Total amount of dredged material in the reach (tons/yr),

Qs_{sto}^{i} = Total amount of sediment deposited in the reach (tons/yr),

Qs_{bw}^{i} = Total sediment discharge into backwaters in the reach (tons/yr), and

n = Number of tributaries in the reach.

The upstream limit of the sediment budget was chosen as the sediment measurement station at McGregor, Iowa (RM 633.4) in Pool 10. The upstream sediment input (Qs^{i-1}) for the sediment budget could thus be estimated from the record of suspended sediment transport measurements at that station. Equation 6-1 was applied to determine the outflow of sediment from Pool 10 (and input to Pool 11). In a similar manner, the input and output of sediment from each analysis reach was determined.

Adequate suspended sediment measurement records from which the average annual total sediment transport along the Mississippi River can be quantified are available for four measurement stations within the sediment budget study area (East Dubuque, Burlington, Keokuk, and Grafton). The results of the sediment budget can be compared against the total sediment load determined at these locations from measured data. Since the sediment transport at these locations is known (measured), the difference between the predicted and measured sediment load must be attributed to factors that are not accounted for in the sediment budget. Since, the sediment budget only considers the storage of sediment within the main channel, the difference between the predicted and measured sediment load for present purposes is assumed to be attributed to sediment storage in the backwater area of the navigation pools. Combining the results of the sediment budget analysis with backwater area estimates derived from plan form analysis, estimates of sediment accumulation rates in off-main channel areas (backwater areas) are obtained.

6.1.1 Assumptions

The following assumptions are made in the sediment budget analysis:

- The storage of sediment along the main channel is adequately represented by historic cross section data at locations that are, in most cases, 1 mile apart. The spacing of the cross section data employed was the highest density allowed by the data.

- Where measurements are unavailable, the bed load of the Mississippi River and major tributaries was assumed equal to 10 percent of the total load. This assumption was used in the Upper Mississippi River Comprehensive Basin Study (USACE (1970), Appendix G) and was also used by Nakato (1981a) and Hsu (1982).

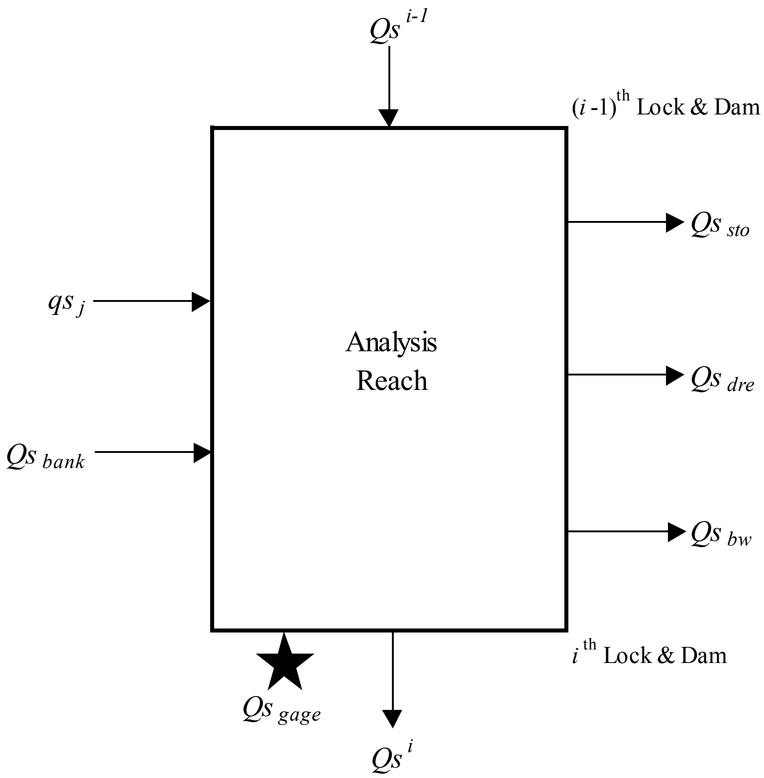
- The sediment supply from ungaged tributary areas to each reach was estimated to have same sediment yield as gaged tributary areas for the reach.

- Sediment supplies from bank erosion are assumed to be zero. A comprehensive bank erosion study was published by USACE (1997) estimates that approximately 14% of Upper Mississippi River banks were actively eroding in 1995. However, the report does not estimate the rate at which banks are eroding, or the corresponding supply of sediment to the river, due to the complexity of the processes involved.

- The density of main channel sediment is assumed equal to 96.3 lb/ft^3. This assumption is consistent with Nakato (1981a) and Hsu (1982). The density of backwater sediment is assumed to be 96.3 lb/ft^3. It is recognized, that the density of sediment deposits is variable with, among other things, location, age and type of material. Considering the variability, use of a typical value is reasonable. The density of dredge material is assumed to be 96.3 lb/ft^3 which is expected to be a good estimate as the main channel bed is mostly sand.

The sensitivity of the sediment budget analysis results to these assumptions is analyzed in Section 6.2.3.

SEDIMENT BUDGET CONCEPT



For reach *i*:

$$Qs^{i} - Qs^{i-1} = \sum_{j=1}^{n} qs_{j} + Qs_{bank} - Qs_{dre} - Q_{sto} - Qs_{bw}$$

where

- Qs^{i} : Total sediment discharge out of the i^{th} analysis reach (tons/yr)
- Qs^{i-1} : Total sediment discharge into the i^{th} analysis reach (tons/yr)
- qs_{j} : Total sediment discharge from the j^{th} tributary of the analysis reach (tons/yr)
- Qs_{bank} : Total sediment discharge from bank erosion in the analysis reach (tons/yr)
- Qs_{dre} : Total amount of dredged material in the analysis reach (tons/yr)
- Qs_{sto} : Total amount of sediment deposited in the analysis reach (tons/yr)
- Qs_{bw} : Total sediment discharge into backwaters in the analysis reach (tons/yr)
- n : Number of tributaries in the reach
- Qs_{gage} : Total sediment discharge at measurement station (tons/yr)

At a sediment gage:

If $Qs^{i} > Qs_{gage}$, then

$Qs^{i} - Qs_{gage}$ = Backwater sedimentation

Figure 6-1: Sediment budget concept.

6.1.2 Main Channel Sediment Storage

As sediment is transported along the UMR, it is deposited and eroded in varying amounts at various locations along the channel. To characterize the conditions of sediment storage along the UMR and to quantify the net amount of sediment that comes into or out of storage, a comparison of historic cross sections was conducted. Details of the historic cross section comparison are presented in Section 5.5. The availability of data and the length of each analysis reach determined the locations and number of historic cross-sections used in the comparison. On average, historic cross-sections used in the comparisons are located one mile apart.

The coverage of the river is variable among the available historic cross sections data sets. Few of the available historic cross section data sets were found to cover both the main channel and backwater areas. Most of the available data sets do not cover backwater areas. For consistency, the sediment storage along the UMR could only be evaluated for the main channel portion of the river channel. Consequently, the sediment budget does not directly consider the storage of sediment outside of the main channel. Sedimentation in off-main channel areas (backwaters) required indirect quantification.

The calculation of sediment storage along the main channel involved the comparison of historic cross sections to determine the net area of erosion or deposition at that location along the channel. Only the portion of the channel within the main channel banks was included in the comparison. The areas of erosion or deposition determined at sequential cross sections along the channel were used in an average-end-area calculation to determine the volume of erosion or deposition between the cross sections. The calculated volume of erosion or deposition between all cross sections within an analysis reach was summed to determine the net change in sediment storage within the reach over the timeframe represented by the available historic cross sections.

6.1.3 Historic Dredging

The amount of sediment that has been removed from the UMR main channel through dredging activities was estimated based on available records. Information on the date, location, and volume of dredging and associated locations of dredge material placement was collected for each analysis reach. Summaries of the collected dredge material data for the entire UMR were previously presented in Section 5.2.5.

In view of the available records of historic dredging activities, and general knowledge about historic dredge material placement procedures, the assumption that historic dredging activities along the UMR effectively removed sediment from the main channel is questionable (see detailed discussion in Section 5.4.4). Accordingly, the removal of historic dredging volumes from the sediment budget for an analysis reach may or may not be appropriate. To assess the impact of the assumption on the results of the sediment budget, the budget was calculated twice. First, the budget was calculated in accordance with the sediment budget concept, removing historic dredging volumes from the budget. Second, the budget was recomputed, assuming that dredged materials were not removed from the budget. Further exploration of this issue is provided in Section 6.2.3

6.1.4 Sediment Transport Estimates

Available sediment transport data was collected and evaluated to develop estimates (Nakato, unpublished, 1998) of the average annual total sediment load transported along the mainstem of UMR and supplied from its tributaries. Details of the procedures used to develop the total load sediment transport estimates are provided in Section 5.3. Estimates of tributary total load sediment transport were also identified from previous studies (Nakato, 1981a; Hsu, 1982; Rose, 1992). The average annual sediment supply for each tributary to an analysis reach was summed to determine the total sediment supply to that reach. It is noted that, in most cases, the sediment transport and discharge measurement records upon which the estimates are based are for the period of the 1970s to present.

6.2 RESULTS

The results of the sediment budget analysis are presented in the following two subsections in two different ways to analyze two different issues. First, in Section 6.2.1, Historic Change, the sediment budget starts at the sediment measurement station at McGregor, near the downstream end of Pool 10, and extends to a downstream sediment measurements station at Grafton, in Pool 26. The sediment budget was calculated for two time periods: Time Period I (approximately immediately post-dam to mid-1950s) and Time Period II (approximately mid-1950s to 1995). Both dredging and main channel sediment storage data are available for both time periods. Tributary and mainstem suspended sediment loads are only available for the second time period. The sediment budget is therefore not updated at the mainstem gages but routed through the whole reach. This version of the sediment budget allows for analysis of changes in sediment transport between the two time periods since the methods of computing sediment transport for the two periods are the same. The resultant sediment budget is presented in Table 6-1 and Table 6-2. An analysis of decrease in tributary sediment input is presented in Figure 6-2.

Second, in Section 6.2.2, the sediment budget is calculated for Time Period II by restarting the sediment budget at each mainstem sediment measurement station. This version of the sediment budget provides the best estimate of sediment transport conditions in the river at present. It provides an estimate of sediment input and output for each pool as well as an estimation of sedimentation in backwater areas. The resultant sediment budget is presented in Table 6-4. The table effectively represents four independent sediment budgets between adjacent mainstem sediment measurements stations.

6.2.1 Historic Change

To evaluate historic changes in the sediment transport characteristics of the UMR, sediment budgets were prepared for two general time periods. Period I extends from immediate post-locks and dams impoundment (late 1930s) to the mid-1950s. Period II covers the timeframe from the mid-1950s to present. Generally, the time periods evaluated were dictated by the availability of adequate cross section data.

The sediment budget starts at the sediment measurement station at McGregor, near the downstream end of Pool 10, and extends downstream to the sediment measurement station at Grafton, in Pool 26. The budget calculations proceed from upstream to downstream. For each analysis reach, the sediment budget is adjusted by main channel sediment storage and dredging amounts. The resultant sediment budgets are presented in Table 6-1 and Table 6-2.

For certain analysis reaches, the available historical cross section data was limited. In such cases, it was necessary to use the same data for main channel storage for both analysis periods. The dates of the cross section coverage and the dredging records are shown in column 4 in the sediment budget tables. It is also noted that the available sediment transport measurement data for the mainstem and tributaries are limited to recent years. Therefore, the same estimates of average annual mainstem transport and tributary sediment inputs were used for both analysis periods. The period of record used to develop mainstem sediment transport and tributary sediment input estimates is shown in Table 5-3. By comparing the results of the sediment budget for both time periods several conclusions can be drawn regarding historic sediment transport conditions.

Under the assumption that dredging materials are effectively removed from the main channel, the value of each term of equation 6-1 is shown in Table 6-1 for both analysis periods (in this version of the budget $Qs^{\prime}_{bank}$ and $Qs^{\prime}_{bw}$ are assumed to be zero). The values of each term of equation 6-1, under the assumption that dredging materials are not effectively removed from the main channel, are shown in Table 6-2. The specific time period for which the main channel sediment storage and dredging volumes were determined are shown in the tables.

As seen in both Table 6-1 and Table 6-2, significantly greater main channel sedimentation and dredging occurred along the UMR during Period I compared to Period II. In fact, the calculated sediment output is about 50 percent larger in Period II than in Period I. As the <u>same</u> tributary sediment inputs to the sediment budget were used in the analysis for both time periods, the difference in sediment output between the periods can be attributed to several factors. These include higher historic sediment supplies from tributaries in Period I, and reduced dredging volumes and possibly more efficient main channel sediment transport in Period II.

In Table 6-1 and Table 6-2, the sediment budget is calculated for both time periods by using measured quantities for main channel storage and dredging. However, the tributary input is only known for the second time period and therefore the same tributary input was used for both time periods in the tables. However, this assumption is not considered realistic, since the sediment output at Grafton is seen to be lower for the first time period. A variety of qualitative and quantitative evidence support the conclusion that historic sediment loads along the UMR were larger than current amounts. Data from Keown et al. (1986) indicate that suspended sediment loads for the UMR at Hannibal, MO decreased by about 32 percent between 1953 and 1967 (see discussion in Section 5.3.3). This is explored in Figure 6-2, where the decrease in tributary sediment input is plotted as a function of the decrease in sediment load at Grafton. Table 6-3 shows an example of the calculation for an assumed 32% decrease in sediment load at Grafton. The calculations assume that 50% of the dredged material is removed from the river and the backwater accumulation decreased by 33% between the time periods (see discussion in following section). Figure 6-2 shows that if it is assumed that the sediment load at Grafton was unchanged between the time periods, a 30% decrease in tributary sediment load would be required. For a 30 to 40% decrease in sediment load at Grafton, the tributary sediment load would have decreased by 40 to 50% between the two time periods.

Several sources of data support the conclusion that sediment supplies to the UMR are decreasing. First, as discussed in Section 5.4.6, the number of reservoirs that can trap sediment on the tributaries to the UMR has increased by approximately 80 percent since the construction of the 9-ft Channel Project. Second, data of the National Resource Conservation Service on historic watershed erosion (NRCS, 1994) previously discussed in Section 3.3 indicate decreasing sediment supply from agricultural land use in each state within the UMR basin. Third, the historic dredging data for the UMR presented in Section 5.4.4, demonstrate decreasing amounts of dredging since construction of the 9-ft Channel Project. Finally, measured sedimentation rates are decreasing as is shown in Table 6-5 and in Figure 6-3.

Table 6-1: Sediment budget for Upper Mississippi River with dredged material taken out (the river is not able to reintroduce the dredge material).

Period I - Post Impoundment to mid-1950s

Pool No.	RM for L&D's (mi)	Pool Length (mi)	Time Period (1)		Input to Pool (tons/yr) (2)	Input from Tributaries (tons/yr) (2)	Main Channel Storage (tons/yr) (3)	Dredging (tons/yr)	Output from Pool (tons/yr)
McGrego	633.4								
10	615.1	29.4	1975	1995	2,094,000	649,212	191,600	23,425	2,528,187
11	583.0	51.7	1938	1951	2,528,187	2,192,226	695,857	273,474	3,751,082
12	556.7	42.3	1939	1995	3,751,082	133,690	-214,385	42,296	4,056,860
13	522.5	55.0	1945	1990	4,056,860	2,076,183	149,698	127,013	5,856,332
14	493.3	47.0	1938	1944	5,856,332	837,033	176,295	198,849	6,318,221
15	482.9	16.7	1947	1952	6,318,221	29,894	366,415	103,556	5,878,145
16	457.2	41.4	1938	1949	5,878,145	1,790,649	793,750	61,287	6,813,756
17	437.1	32.3	1938	1954	6,813,756	16,279	303,607	92,407	6,434,022
18	410.1	43.5	1938	1995	6,434,022	3,719,355	-199,241	144,152	10,208,465
19	364.2	73.9	1938	1946	10,208,465	3,598,834	5,022,655	359,722	8,424,922
20	343.2	33.8	1937	1950	8,424,922	7,882,322	-2,511	112,142	16,197,614
21	324.9	29.4	1938	1953	16,197,614	796,496	561,113	168,152	16,264,845
22	301.2	38.1	1938	1954	16,264,845	2,219,078	846,106	244,184	17,393,633
24	273.4	44.7	1977	1995	17,393,633	1,260,376	-1,070,804	242,412	19,482,401
25	241.5	51.3	1977	1995	19,482,401	407,769	1,587,598	758,336	17,544,236
Grafton	218.0	37.8	1971	1995	17,544,236	7,681,670	206,507	721,913	24,297,486
Sum						35,291,066	9,414,260	3,673,319	

Period II - Mid-1950s to Present

L&D No.	RM for L&D's	Pool Length (km)	Time Period (1)		Input to Pool (tons/yr) (2)	Input from Tributaries (tons/yr) (2)	Main Channel Storage (tons/yr) (3)	Dredging (tons/yr)	Output from Pool (tons/yr)
McGrego	633.4								
10	615.1	29.4	1975	1995	2,094,000	649,212	191,600	23,425	2,528,187
11	583.0	51.7	1951	1995	2,528,187	2,192,226	655,679	69,591	3,995,143
12	556.7	42.3	1939	1995	3,995,143	133,690	-214,385	42,296	4,300,921
13	522.5	55.0	1945	1997	4,300,921	2,076,183	149,698	54,579	6,172,827
14	493.3	47.0	1944	1995	6,172,827	837,033	-428,872	77,114	7,361,618
15	482.9	16.7	1951	1995	7,361,618	29,894	-15,983	2,566	7,404,928
16	457.2	41.4	1949	1995	7,404,928	1,790,649	-89,124	45,264	9,239,438
17	437.1	32.3	1954	1995	9,239,438	16,279	-135,717	39,546	9,351,888
18	410.1	43.5	1938	1995	9,351,888	3,719,355	-199,241	144,152	13,126,332
19	364.2	73.9	1948	1995	13,126,332	3,598,834	-56,938	115,869	16,666,234
20	343.2	33.8	1950	1995	16,666,234	7,882,322	-434,012	133,797	24,848,771
21	324.9	29.4	1953	1995	24,848,771	796,496	-176,589	167,969	25,653,887
22	301.2	38.1	1954	1995	25,653,887	2,219,078	-473,325	156,556	28,189,734
24	273.4	44.7	1977	1995	28,189,734	1,260,376	-1,070,804	242,412	30,278,502
25	241.5	51.3	1977	1995	30,278,502	407,769	1,587,598	758,336	28,340,337
Grafton	218.0	37.8	1971	1995	28,340,337	7,681,670	206,507	721,913	35,093,587
Sum						35,291,066	-503,908	2,795,386	

(1) Time period used to determine main channel storage and dredging amounts
(2) The same mainstem and tributary sediment input is used for both analysis periods
(3) Main channel storage amount for Pool 13 are from Rogala (unpublished)

Table 6-2: Sediment budget for Upper Mississippi River with dredge material left in (the river is able to reintroduce the dredge material).

Period I - Post Impoundment to mid-1950s									
Pool No.	RM for L&D's (mi)	Pool Length (mi)	Time Period (1)		Input to Pool (tons/yr) (2)	Input from Tributaries (tons/yr) (2)	Main Channel Storage (tons/yr) (3)	Dredging (tons/yr)	Output from Pool (tons/yr)
McGrego	633.4								
10	615.1	29.4	1975	1995	2,094,000	649,212	191,600	23,425	2,551,612
11	583.0	51.7	1938	1951	2,551,612	2,192,226	695,857	273,474	4,047,981
12	556.7	42.3	1939	1995	4,047,981	133,690	-214,385	42,296	4,396,056
13	522.5	55.0	1945	1990	4,396,056	2,076,183	149,698	127,013	6,322,540
14	493.3	47.0	1938	1944	6,322,540	837,033	176,295	198,849	6,983,278
15	482.9	16.7	1947	1952	6,983,278	29,894	366,415	103,556	6,646,757
16	457.2	41.4	1938	1949	6,646,757	1,790,649	793,750	61,287	7,643,657
17	437.1	32.3	1938	1954	7,643,657	16,279	303,607	92,407	7,356,328
18	410.1	43.5	1938	1995	7,356,328	3,719,355	-199,241	144,152	11,274,924
19	364.2	73.9	1938	1946	11,274,924	3,598,834	5,022,655	359,722	9,851,103
20	343.2	33.8	1937	1950	9,851,103	7,882,322	-2,511	112,142	17,735,936
21	324.9	29.4	1938	1953	17,735,936	796,496	561,113	168,152	17,971,319
22	301.2	38.1	1938	1954	17,971,319	2,219,078	846,106	244,184	19,344,291
24	273.4	44.7	1977	1995	19,344,291	1,260,376	-1,070,804	242,412	21,675,471
25	241.5	51.3	1977	1995	21,675,471	407,769	1,587,598	758,336	20,495,642
Grafton	218.0	37.8	1971	1995	20,495,642	7,681,670	206,507	721,913	27,970,805
Sum						35,291,066	9,414,260	3,673,319	

Period II - Mid-1950s to Present									
L&D No.	RM for L&D's	Pool Length (km)	Time Period (1)		Input to Pool (tons/yr) (2)	Input from Tributaries (tons/yr) (2)	Main Channel Storage (tons/yr) (3)	Dredging (tons/yr)	Output from Pool (tons/yr)
McGrego	633.4								
10	615.1	29.4	1975	1995	2,094,000	649,212	191,600	23,425	2,551,612
11	583.0	51.7	1951	1995	2,551,612	2,192,226	655,679	69,591	4,088,159
12	556.7	42.3	1939	1995	4,088,159	133,690	-214,385	42,296	4,436,234
13	522.5	55.0	1945	1997	4,436,234	2,076,183	149,698	54,579	6,362,718
14	493.3	47.0	1944	1995	6,362,718	837,033	-428,872	77,114	7,628,623
15	482.9	16.7	1951	1995	7,628,623	29,894	-15,983	2,566	7,674,500
16	457.2	41.4	1949	1995	7,674,500	1,790,649	-89,124	45,264	9,554,274
17	437.1	32.3	1954	1995	9,554,274	16,279	-135,717	39,546	9,706,269
18	410.1	43.5	1938	1995	9,706,269	3,719,355	-199,241	144,152	13,624,865
19	364.2	73.9	1948	1995	13,624,865	3,598,834	-56,938	115,869	17,280,637
20	343.2	33.8	1950	1995	17,280,637	7,882,322	-434,012	133,797	25,596,971
21	324.9	29.4	1953	1995	25,596,971	796,496	-176,589	167,969	26,570,056
22	301.2	38.1	1954	1995	26,570,056	2,219,078	-473,325	156,556	29,262,459
24	273.4	44.7	1977	1995	29,262,459	1,260,376	-1,070,804	242,412	31,593,639
25	241.5	51.3	1977	1995	31,593,639	407,769	1,587,598	758,336	30,413,810
Grafton	218.0	37.8	1971	1995	30,413,810	7,681,670	206,507	721,913	37,888,973
Sum						35,291,066	-503,908	2,795,386	

(1) Time period used to determine main channel storage and dredging amounts
(2) The same mainstem and tributary sediment input is used for both analysis periods
(3) Main channel storage amount for Pool 13 are from Rogala (unpublished)

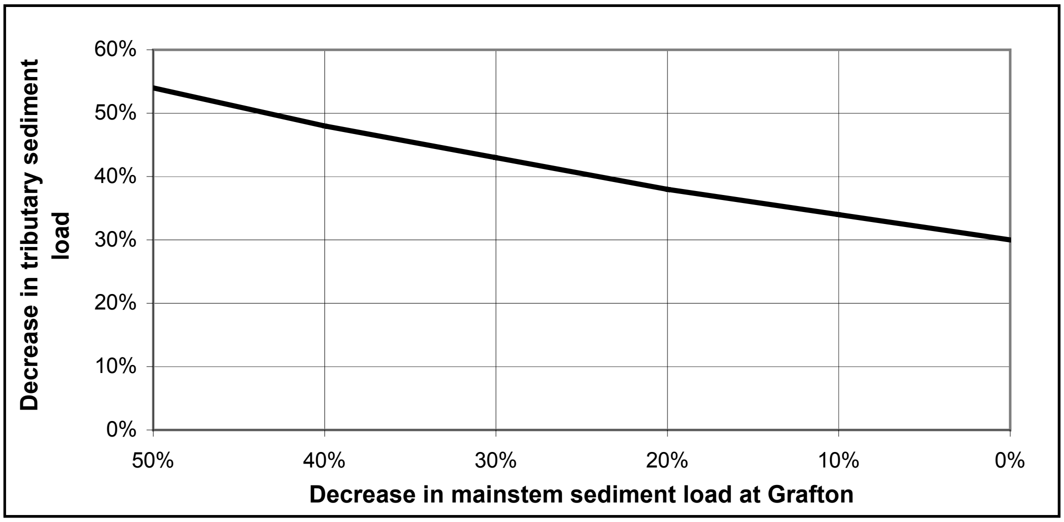


Figure 6-2: Decrease in tributary sediment load as a function of sediment load decrease at Grafton based on the sediment budget shown in Table 6-1 (see example of calculation in Table 6-3).

Table 6-3: An example of calculation for decrease in tributary sediment load based on assumed decrease in sediment load at Grafton. The table shows example for 32% decrease at Grafton (see Figure 6-2).

	Period I			Period II			
	Measured (ton/yr)	Adjustment Factor	Adj. Values (ton/yr)	Measured (ton/yr)	Adjustment Factor	Adj. Values (ton/yr)	Decrease %
At McGregor	2,094,000	1.00	2,094,000	2,094,000	1.00	2,094,000	0%
Tributary Sed. Input*	35,291,066	1.79	63,105,775	35,291,066	1.00	35,291,066	44%
Storage	9,414,260	1.00	9,414,260	-503,908	1.00	-503,908	
Dredging	3,673,319	0.50	1,836,660	2,795,386	0.50	1,397,693	24%
Backwater Accum.	9,660,000	1.50	14,490,000	9,660,000	1.00	9,660,000	33%
At Grafton**	14,637,486		39,458,855	25,433,587		26,831,280	32%

* Unknown for time period I
** Decrease between time periods is unknown

6.2.2 Present Sediment Transport Conditions

A second version of the sediment budget was developed to best describe current sediment transport conditions along the UMR as well as provide estimates for backwater sediment accumulation. The budget provides detailed information on the sediment supply to each pool, the change in sediment storage within the pool, dredging, and sediment transport out of the pool. The sediment budget is adjusted at locations along the mainstem where sediment transport has been measured. The adjustment at each sediment measurement station provides an estimate of the amount of sedimentation within backwater areas. The results of the sediment budget are presented in Table 6-4. In Table 6-4, Column (1), sediment measurements at the sediment measurement stations are listed. To allow comparison between stations, measurements for consistent time periods of records are given for successive stations.

6.2.2.1 Backwater Sediment Accumulation Rates

The sediment accumulation rate in the backwater areas of navigation pools was determined by dividing the difference between the measured sediment load and the sediment transport predicted by the sediment budget at sediment measurement stations by the area of the off-main channel (backwater) area between the successive measurement stations. The area of the backwater was determined by subtracting the water area represented by the main channel cross sections from the total water area measured from 1989 aerial photography for each pool. The calculated sedimentation rate for the backwater area between sediment measurement station locations is shown in Table 6-4. The backwater sediment accumulation rates shown in the table best reflect recent conditions. Since a significant record of sediment transport measurements for the mainstem and tributaries of the UMR are only available for recent years, historic sediment accumulation rates could not be defined in this manner.

Column (12) of Table 6-4 presents estimates of backwater sediment accumulation rates based on dredged material not being removed from the sediment budget. Column (13), on the other hand, presents estimates of backwater sediment accumulation rates based on dredged materials being removed from the sediment budget. As seen in the table, the removal of dredge material from the sediment budget reduces estimated backwater accumulation rates significantly where the associated dredging amounts are large. However, the overall magnitude of the average sediment accumulation rate is small in either case. Generally, the results indicate that recent, system-wide backwater sedimentation rates are small, on the order of millimeters per year.

A summary of sedimentation rate estimates along the UMR by other investigators is shown in Table 6-5. The table shows that previous estimates of backwater sedimentation rates (Nakato, 1981a; McHenry et al, 1984; Knox and Faulkner, 1994; Rogala and Boma, 1996; Rogala and James, 1997) vary considerably, ranging from several centimeters per year to less than 0.5 cm/year. The results of the current study support lower estimates for recent sedimentation rates. The sedimentation rates from the table are plotted in Figure 6-3. Although the estimates from all the studies are presented in the figure, it is understood that the involved estimates are not always directly comparable as the methods used in their development varied widely and procedures used for selection of sampling location and size of sampling area are diverse. However, a general decreasing trend in the sedimentation rate for the data set is detected. It is noted that the estimates from the current study reflect average conditions for all off-main channel areas located between sediment measurement stations. Localized sediment deposition rates can vary significantly from the average.

Table 6-4: Backwater sediment accumulation rates derived from sediment budget.

Pool No.	RM for L&D's	Pool Length / Sediment Gaging Station (mi)	Sediment Load @ Gaging Station (tons/yr) (1)	Time Period (2)		Input to Pool (tons/yr) (3)	Input from Tributaries (tons/yr) (4)	Main Channel Storage (tons/yr) (5)	Dredging (tons/yr) (6)	Calculated Sediment Transport (tons/yr) (7)	Output from Pool (tons/yr) (8)	Total Water Area (mi^2) (9)	Back-water Area (mi^2) (10)	Sediment Transport Difference (tons/yr) (11)	Backw. Accum. (dredge left in) (cm/year) (12)	Backw. Accum. (dredge taken out) (cm/year) (13)
10	633.4	McGregor	2,094,000	1976	1995											
10	615.1			1975	1995	2,094,000	649,212	191,600	23,425		2,551,612	14.0	10.3			
11	583.0	32.1		1951	1995	2,551,612	2,192,226	655,679	69,591		4,088,159	29.7	21.7			
12				1939	1995	4,088,159	0	-78,384	1,487			1.4	0.9			
12	580.1	E. Dubuque	5,000,056	1976	1996					4,166,543		45.2	32.9	-833,513	-0.05	-0.05
12	580.1	E. Dubuque	5,266,333	1968	1996											
12	556.7	26.3		1939	1995	5,266,333	133,690	-136,001	40,809		5,536,024	15.7	9.4			
13*	522.5	34.2		1945	1997	5,536,024	2,076,183	149,698	54,579		7,462,509	35.8	27.4			
14	493.3	29.2		1944	1995	7,462,509	837,033	-428,872	77,114		8,728,414	14.8	7.3			
15	482.9	10.4		1951	1995	8,728,414	29,894	-15,983	2,566		8,774,291	5.5	1.9			
16	457.2	25.7		1949	1995	8,774,291	1,790,649	-89,124	45,264		10,654,064	17.2	8.2			
17	437.1	20.1		1954	1995	10,654,064	16,279	-135,717	39,546		10,806,059	10.1	4.8			
18	410.1	27.0		1938	1995	10,806,059	3,719,355	-199,241	144,152		14,724,655	17.3	8.3			
19				1948	1995	14,724,655	356,667	149,369	61,411			3.9	3.4			
19	403.1	Burlington	11,367,667	1968	1996					14,931,953		120.3	70.7	3,564,286	0.05	0.04
19	364.2	45.9		1948	1995	11,367,667	3,242,167	-206,307	54,458		14,816,140	38.8	7.5			
20				1950	1995	14,816,140	0	0	0			0.3	0.0			
20	364.1	Keokuk	13,888,889	1968	1996					14,816,140		39.1	7.5	927,251	0.23	0.22
20	364.1	Keokuk	18,055,111	1991	1994											
20	343.2	21.0		1950	1995	18,055,111	7,882,322	-434,012	133,797		26,371,445	11.0	2.4			
21	324.9			1953	1995	26,371,445	796,496	-176,589	167,969		27,344,531	11.1	4.3			
22	301.2	23.7		1954	1995	27,344,531	2,219,078	-473,325	156,556		30,036,934	11.8	2.7			
24	273.4	27.8		1977	1995	30,036,934	1,260,376	-1,070,804	242,412		32,368,114	16.6	8.2			
25	241.5	31.9		1977	1995	32,368,114	407,769	1,587,598	758,336		31,188,284	23.0	12.4			
26				1971	1995	31,188,284	7,681,670	206,507	721,913			13.4	6.5			
26			32,641,667	1991	1994					38,663,448		64.8	29.9	6,021,781	0.31	0.20
26	202.9	38.6						-116,098	2,767			12.4	4.5			

(1) Average annual sediment load at gage determined from suspended sediment measuremen
(2) Time period for which the main channel storage and dredging amount were calculated.
(3) Equal to either (1) or (8).
(4) Average annual sediment load determined from suspended sediment measurements.
(5) Calculated from cross section comparison for time periods listed in column (2).
(6) Average annual dredging determined from dredging records for time period in column (2).
(7) Sediment transport at gage calculated using Equation (6-1).
(8) Sediment transport output from reach calculated using Equation (6-1).
(9) Calculated from 1989 aerial photography.
(10) Column (9) less the area covered by the cross sections used in column (5).
(11) Column (7) less column (1).
(12) Column (11) divided by column (10).
(13) Result with dredged material removed from the system.
* Bed elevation changes from Rogala (Unpublished)

Table 6-5: Summary of UMR sedimentation rate estimates (see also Figure 6-3).

Source Reference	Location	Estimated Sedimentation Rate (cm/year)	Applicable Time Period	Comments
Current Study	Lower Pool 11	1.56	1938 - 1951	Average of thirteen cross sections (RM 584 - 597) for backwater areas
		0.34	1951 - 1995	
	RM 403 to 580 Pools 12 -19	0.05 (0.04)*	Primarily ~mid-1940s to 1995	Average for backwater areas derived from sediment budget, assuming dredged material left in *(dredge material taken out).
	RM 364 to 403 Pools 19 - 20	0.23 (0.22)*	Primarily ~1950 to 1995	
	RM 218 to 364 Pools 20 - 26	0.31 (0.20)*	Primarily ~mid-1960s to 1995	
Rogala and James (1997)	Pool 8	0.46	1989 – 1996	Mean rate for 25 backwater transects
Rogala and Boma (1996)	Pools 4, 8, 13	0.25	1989 - 1996	Average based on 42 backwater transects, excluding dredge cuts
Knox and Faulkner(1994) (upstream from the confluence with MR along Buffalo River)	Pool 4: Lower Buffalo River (Silt Range 163)	2.0	1935 - 1954	Cesium-137 dating, Based on two core holes (about 1000 m upstream)
		0.9	1954 - 1992	
	Pool 4: Lower Buffalo River (Silt range 158)	3.3	1935 - 1945	Cesium-137 dating, Based on entire transect (about 200 m upstream)
		1.4	1945 - 1954	
McHenry et al. (1984)	Pools 4, 5, 5A, 6, 7, 8, 9, 10	3.4	1954-1964	Cesium-137 dating, Average based on 47 profiles.
	Pools 4, 5, 5A, 6, 7, 8, 9, 10	1.8	1965 - 1975	
Nakato (1981a)	Pools 11,12,14,16,17, 20, 21, 22	1.62	Primarily 1930s - 1950s	Average rate based on nineteen cross sections for selected backwater areas

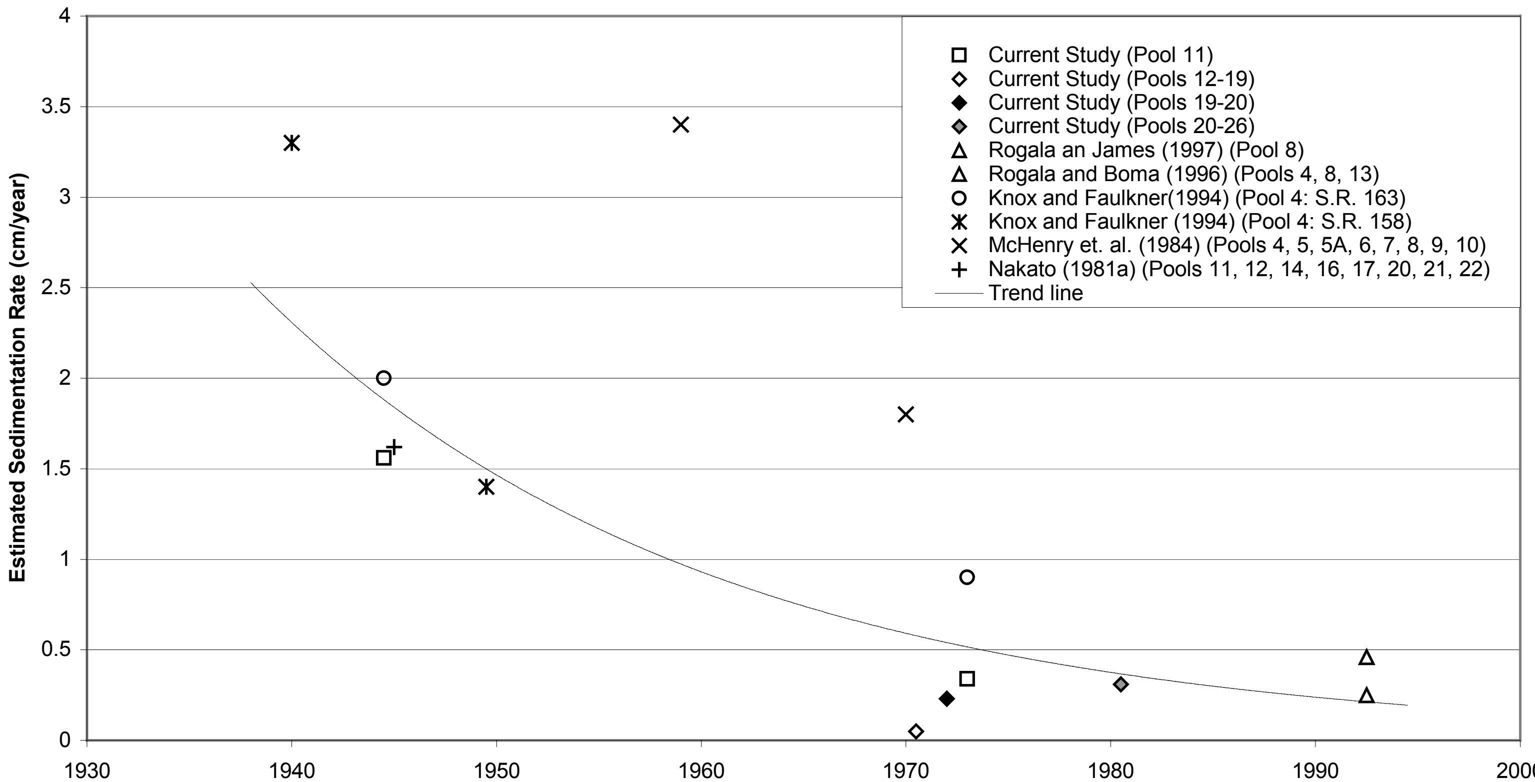


Figure 6-3: Summary of UMR sedimentation rate estimates shown in Table 6-5.

6.2.3 Sensitivity Analysis

An estimate of backwater sediment accumulation based on the sediment budget (Equation 6-1) was presented in Table 6-4. In this section a sensitivity analysis is presented to analyze the influences of the assumptions made in Section 6.1.1 and other possible uncertainty about the terms in Equation 6-1 on the estimated backwater sediment accumulation rates derived from the sediment budget in Section 6.2.2.1. This will be accomplished by identifying the source of uncertainty for each of the terms in Equation 6-1. An estimate of the range for the uncertainty for each variable is then developed. The potential range (sensitivity) for backwater sediment accumulation rate was calculated by varying each of the involved variables over its estimated range of uncertainty. Finally, an upper bound for the backwater sediment accumulation rate estimates is calculated by setting all the involved variables to their maximum values.

In the following paragraphs the uncertainties associated with each variable in Equation 6-1 are discussed (see also summary in Table 6-6) as well as the resulting sensitivity on the backwater sediment accumulation rates:

Sediment discharge from tributaries. The tributary sediment input term has uncertainty associated with the data calculated from sediment measurements on the tributaries. The source of the uncertainty is mainly due to relatively short data records and the variability of sediment measurements. The range of variability for the tributary sediment input term is estimated to be ±20%. The results for the tributary sediment sensitivity analysis are shown in Figure 6-4 (a). The abscissa shows the normalized change in the tributary sediment input and the ordinate shows the resulting normalized change in the backwater sediment accumulation rate. For both axes the subscript zero refers to the number used in the sediment budget. The figure shows that if the tributary sediment input is underestimated by 20% the backwater accumulation would increase about twofold for the reach upstream of Grafton and about 50% for the Burlington reach. At the other extreme, if the tributary sediment input is overestimated by 20%, there would be no backwater accumulation at Grafton and 40 to 50% less at Keokuk and Burlington.

Dredging. The dredging term has uncertainty associated with the density of the dredged material, uncertainty in the data measured and reported by the dredge operators, and uncertainty in the reintrainment of the dredged material by the river. The density of dredged material was assumed to be 96.3 lb/ft^3 in the sediment budget analysis. This value is deemed to be a fairly good estimate as the dredge material is mostly sand (see Section 5.3.1). Therefore, a range of ±10% was used to represent the uncertainty associated with the density estimate. The range of uncertainty associated with the reported dredged amounts was estimated to be ±30%. It is observed that the range of uncertainty for the density estimate is smaller than the range for the reported dredged data. The results of the sensitivity analysis for the dredging term are shown in Figure 6-4 (b). The abscissa shows the normalized change in the dredging amounts and the density of dredged material. An abscissa value of 1 represents no reintrainment of dredged material and a value of zero represents complete reintrainment of dredged material (mainstem disposal). The ordinate shows the resulting normalized change in the backwater sediment accumulation rate. For both axes the parameter with subscript zero refer to the numbers used in the sediment budget. If the river is allowed complete access to the dredged material (mainstem disposal) the backwater accumulation for the Grafton reach is expected to be about 1.6 times higher but only about 10 to 20% higher for the Burlington and the Kekouk reaches. Uncertainty in both the density and reported dredge volumes represents less than 10 to 20% changes in backwater accumulation for the analysis reaches.

Main channel storage. The main channel storage term has uncertainty associated with the density of the main channel bed material and the cross section data used to calculate the sediment volumes. The density of the main channel bed material in the sediment budget analysis was assumed to be 96.3 lb/ft^3. This value is deemed to be a fairly good estimate as most of the main channel bed is sand (see Section 5.3.1). Therefore, a range of ±10% was used to represent the uncertainty associated with the density of sediment stored in the main channel. The range of uncertainty associated with the volume calculations from the cross section data was estimated to be ±20%. It is observed that the range of uncertainty for the density is smaller than the range for the cross section data. The results of the sensitivity analysis for the main channel storage term are shown in Figure 6-4 (c). The abscissa shows normalized change in the main channel storage and the main channel density. The ordinate shows the resulting normalized change in the backwater sediment accumulation rate. For both axes parameter with the subscript zero refer to the numbers used in the sediment budget. The figure shows that for the Grafton reach, the backwater accumulation varies by about ±20% and by 5 to 10% at Burlington and Keokuk over the range analyzed.

Mainstem sediment data. The mainstem gage term (see Figure 6-1) has an uncertainty associated with the data obtained by sediment measurements on the mainstem and with the assumption that the suspended load along the mainstem is 0.9 of the total sediment load. The uncertainty associated with the sediment gage data is estimated to be ±10% as the mainstem suspended sediment measurement data are deemed to be fairly good. To explore the sensitivity of backwater sediment accumulation to the ratio of the suspended sediment load to the total load, the ratio was varied from 0.7 to 0.95. The results of the sensitivity analysis are shown in Figure 6-5 (d). The abscissa shows normalized change in the mainstem data and in the ratio of suspended load to the total load (note that there is an inverse relation for these two parameters, so the range 0.7 to 0.95 on the abscissa translates to 1.29 to 0.95 on the abscissa). The ordinate shows the resulting normalized change in the backwater sediment accumulation rate. For both axes the subscript zero refer to the numbers used in the sediment budget. The figure shows that a higher suspended sediment ratio will increase the backwater accumulation, at the extreme from about 15% at Burlington to about 40% at Grafton. A lower ratio will significantly lower the backwater accumulation, with Grafton being the most sensitive.

Bank erosion. Bank erosion was assumed to be zero in the sediment budget as no specific data is available for reasonable estimates. It is believed that main channel sediment storage may partially account for any influence bank erosion may have on the sediment budget as the cross section extends between banks along the main channel. To assess the sensitivity of the backwater sediment accumulation rate to the influence of bank erosion it was estimated that the input from bank erosion could vary between 0 and 20% of the main channel sediment storage input. The results of this analysis are shown in Figure 6-5 (e). The abscissa shows the normalized change in the bank erosion and the ordinate shows the resulting normalized change in the backwater sediment accumulation rate. For both axes the subscript zero refer to the numbers used in the sediment budget. The figure shows that for the highest estimate of the bank erosion, the backwater sediment accumulation of the Grafton reach will increase by about 20% and between 5 to 10% for the Keokuk and Burlington reaches.

Backwater sediment density. In the sediment budget it was assumed that the density of the sediment deposited in the backwater areas was 96.3 lb/ft^3. The sediment density in backwater areas is dependent on many factors and is believed to vary considerably from location to location. To analyze the sensitivity of the density estimate on the backwater sedimentation accumulation rate, a range of 70 to 96.3 lb/ft^3 was used in the sensitivity analysis. The results are shown in Figure 6-5 (f). The abscissa shows the normalized change in the backwater density and the ordinate shows the resulting normalized change in the backwater sediment accumulation rate. For both axes the subscript zero refer to the numbers used in the sediment budget. As expected, the results are the same for the three reaches. For the lowest density, 70 lb/ft^3, the backwater sediment accumulation rate was estimated to be about 40% higher than estimated in the sediment budget.

Table 6-6: Range of the variables in Equation 6-1 used in the sensitivity analysis.

	qs_j Tributary sediment input	Qs_{dre} Dredging	Qs_{sto} Main channel sediment storage	Qs_{gage} Mainstem sediment load	Qs_{bank} Bank erosion	Qs_{bw} Backwater sediment accumulation
Reported / Calculated	Mass	Volume	Volume	Mass	N/A	Volume
Variable	N/A	Density	Density	Suspended sedim. ratio	Magnitude	Density
Value used in sed. budget	N/A	96.3 lb/ft^3	96.3 lb/ft^3	0.9	0	96.3 lb/ft^3
Estimated range	N/A	± 10%	± 10%	0.95 – 0.7	(0-0.2) Qs_{sto}	96.3 – 70 lb/ft^3
Measurement uncertainty	Tributary gage	Measured by dredger	Volume measurement	Mainstem gage	N/A	Calc. from sed. budget
Estimated range	± 20%	± 30%	± 20%	± 10%	N/A	Output

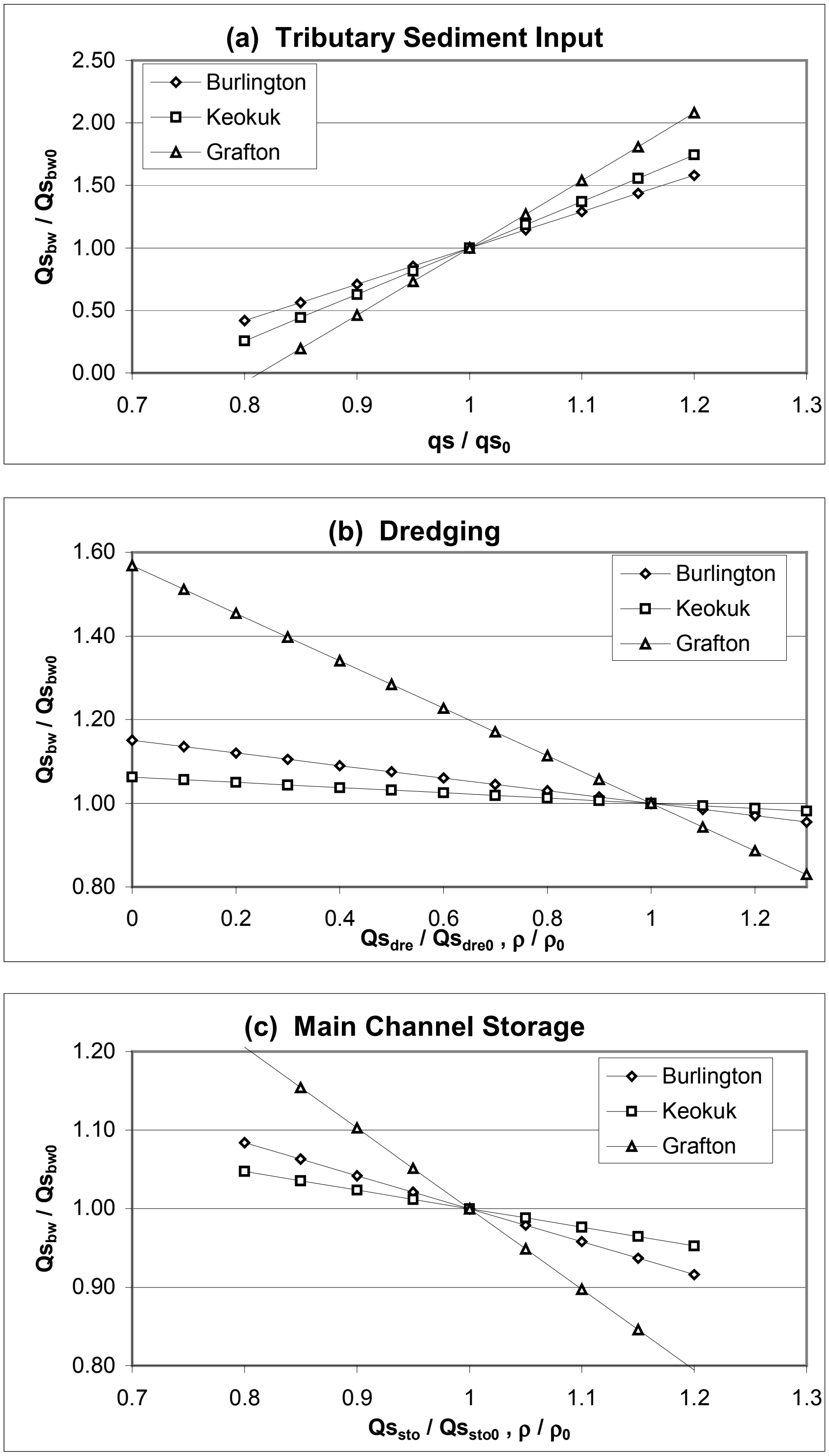


Figure 6-4: Sensitivity analysis of (a) the tributary sediment input, (b) dredging and (c) main channel storage for the sediment budget. The ordinate shows the normalized change in backwater sediment accumulation rate (the footnote zero (0) refers to the value reported for the sediment budget in Section 6.2.2.1) due to the normalized change in the abscissa term(s) over the range defined in the text.

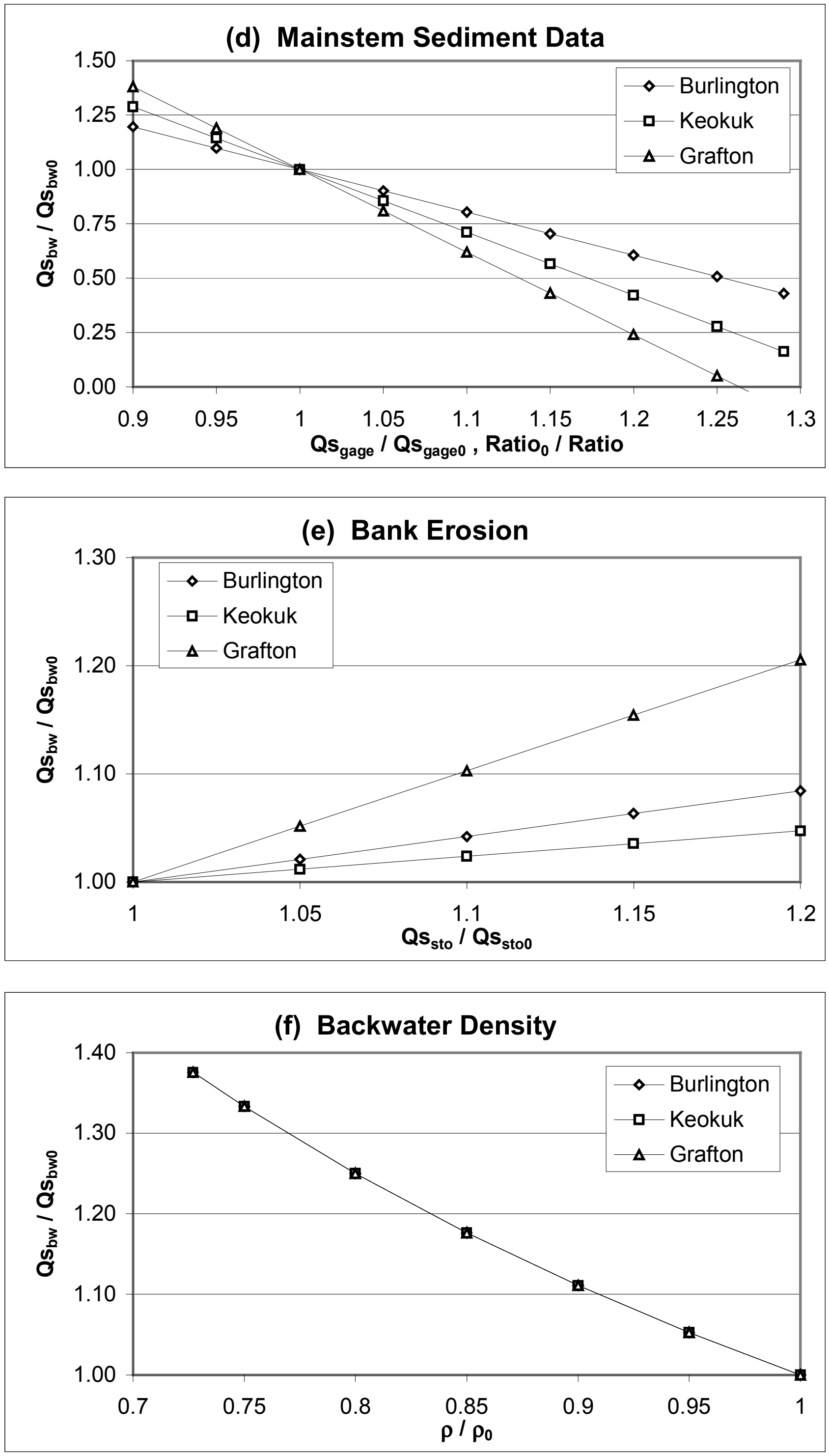


Figure 6-5: Sensitivity analysis of (d) the suspended sediment ratio, (e) bank erosion and (f) backwater density for the sediment budget. The ordinate shows the normalized change in backwater sedimentation accumulation rate (the footnote zero (0) refers to the value reported for the sediment budget in Section 6.2.2.1) due to the normalized change in the abscissa term(s) over the range defined in the text.

Figure 6-6 compares the sensitivity of the backwater sediment accumulation rate as a function of the change of each variable in Equation 6-1 for each of the three reaches considered. For the three reaches, the backwater sediment accumulation rate is most sensitive to the tributary sediment input, with the Grafton reach being the most sensitive. The backwater sediment density is the second most important influence for Burlington and Keokuk reaches. For the Grafton reach, dredging is the second most important factor. The Burlington and Keokuk reaches show similar overall behavior but in the Grafton reach, dredging plays a larger role, which is expected in light of the relatively heavy dredging activity in that reach. The backwater sediment accumulation rate is less sensitive to main channel storage, the mainstem sediment load, the ratio of suspended load to total load and bank erosion.

In the sediment budget, presented in Table 6-4, the backwater sediment accumulation rate is calculated from the sediment budget. The sensitivity analysis, discussed in this section, offers a way to explore the sensitivity of the backwater sediment accumulation rate to each of the involved variables. By setting each of the variables used in the analysis to a value that produces a maximum backwater accumulation, an upper bound is established for the potential maximum backwater sediment accumulation rate for each reach. Table 6-7 lists the results from this analysis. The upper bound for the Burlington and Keokuk reaches are about three times higher than the value calculated in the sediment budget. The Grafton reach the upper bound estimate is almost five times higher. It is emphasized that the upper bound should be looked at as the extreme value for the potential average accumulation, as it represents a value where all the variables that influence the backwater accumulation, would take their respective maximum value. It would for example require that all dredged material be reintrained, all backwater sediments have a density of 70 lb/ft^3, and all sediment input be underestimated by 20% among other things. This is considered unlikely. The calculated upper bound provides a value that can be considered as the maximum theoretical average backwater sediment accumulation rate based on the sediment budget.

Table 6-7: Estimated upper bound for backwater sediment accumulation rate .

Reach	**Backwater sediment accumulation rate**		
	Sediment Budget Estimate (cm/year)	Upper Bound Multiplier	Theoretical Upper Bound (cm/year)
Burlington	0.04	3.0	0.12
Keokuk	0.22	3.2	0.70
Grafton	0.20	4.9	0.98

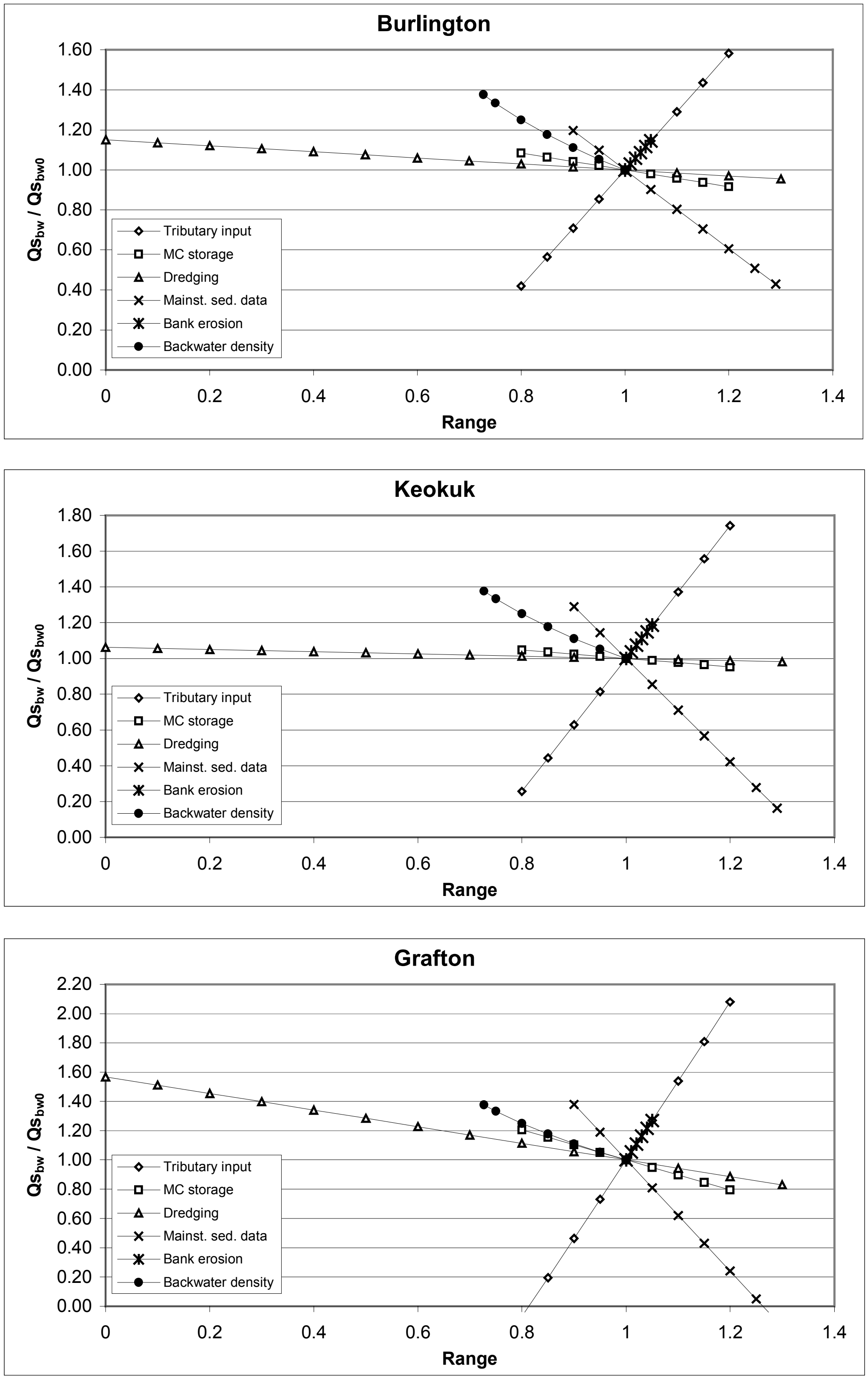


Figure 6-6: Comparison of sensitivity analysis results for each reach in the sediment budget.

7 FUTURE GEOMORPHIC CONDITIONS

As is stated in Chapter 1, one of the main objectives of this study is to estimate the future geomorphic condition in the year 2050. In this section, these predictions are put forth and discussed. The predictions are based on the data analyzed and presented in previous chapters of this report.

The methods and assumption used to predict the future conditions are discussed in Section 7.1. The predictions are presented in Section 7.2. For each Geomorphic Reach, a summary statement discussing the overall geomorphic processes at work for that reach is given. Then, for each pool (or pool portion) within the reach, a detailed discussion is presented focusing on the geomorphic processes influencing the past and future changes in the pool. Following the discussion, the predictions are presented in table format: for each pool portion (Table 7-2), for each geomorphic reach (Table 7-3) and for the whole system (Table 7-4). In Appendix E, maps of concentrated areas of historic geomorphic changes are presented and in Appendix F, predicted areas of concentrated geomorphic change are presented. In addition, in Appendix F, plots for the historic size as well as for the predicted size of each aquatic class, for each pool portion, are given.

7.1 METHOD

The development of an estimate of future geomorphic conditions requires identification of the existing and potential influences on the fluvial system, understanding the controlling geomorphic characteristics of the system, and definition of the direction and magnitude of system response. The preceding chapters of this document were devoted to characterizing each of these requirements. Controlling geomorphic characteristics of the system were described in Sections 5.1 and 5.2. The natural and human influences on the fluvial system were described Section 5.4. The trend of historic geomorphic change, upon which the direction and magnitude of system response was defined, was described in Sections 5.5.

In the following sections, the methods used to synthesize the available information into an estimate of future geomorphic conditions are described. It is emphasized that the estimates of future geomorphic conditions are predictions. The accuracy of the predictions are dependent on the quality of the data available to identify the trend of historic change, the understanding of natural and human influences, and the assumptions made about system response to those influences.

7.1.1 Upper Mississippi River

Extrapolation of historic trends and professional judgement of the involved influences and controlling physical characteristics were used to determine future geomorphic conditions along the UMR. The statistics of historical data used to identify trends in the evolution of aquatic areas are shown in Appendix E. Although estimates of the direction and magnitude of geomorphic change for specific classes of aquatic area can be developed, the prediction of how any individual aquatic feature at a specific location will change is not attempted. Such micro-scale predictions are not feasible as localized change can be influenced by localized random events. Therefore, for example, in areas where wind-wave erosion is expected, the erosion of specific islands is not predicted, but the specific group of islands that will be affected by erosion is identified.

The following general rules were considered in the prediction of future geomorphic conditions:

1. Trends observed from historic plan form analysis statistics were maintained unless other data modified the expected trend.

2. If trends observed from historic plan form analysis indicate the elimination of a particular aquatic class, a minimum residual aquatic class area size of ten percent of its existing value was retained. It is expected, in most cases, that the reduction of the area of an aquatic class will be asymptotic toward zero. This is for example observed in lower Pool 8 demonstrated in Section 5.5.5.4.

3. Where the historical data indicated sedimentation within backwater areas, the historic rate of change was reduced by a factor of two, unless available data suggested otherwise. This rate reduction is consistent with both measured rates of sedimentation along the UMR (McHenry et al., 1984; Knox and Faulkner, 1994) and the results of the sediment budget conducted for the current study (Chapter 6). Furthermore, the comparison of historic cross section data for a backwater in Pool 11, previously presented in Section 5.6, indicates that sedimentation rates have slowed by at least a factor of two.

4. It is recognized that a continuum of evolution can exist between the various aquatic classes. For example, sedimentation of contiguous backwater areas may cause them to become blocked, turning them into isolated backwater areas. Generally, the loss of one aquatic area was reflected as an increase in another aquatic area.

5. In some cases, the potential for change in aquatic area is controlled by the geology. Pools located within relatively narrow, erosion resistant rock gorges were judged to have little ability to adjust or for their aquatic areas to evolve.

6. In certain cases, the historic rate of change for an aquatic class must be modified. For example, if the islands in a pool have been eroded at a certain historic rate, that rate cannot be maintained if the amount of erosion exceeds the island area remaining.

7.1.2 Illinois Waterway

The prediction of channel conditions along the IWW for the Year 2050 was accomplished based on the review, evaluation, and interpretation of results from previous studies and visual comparison of historic plan form information. Only limited historic plan form information was available for use in the development of future geomorphic conditions. Generally, the geologic history of the waterway and a long history of significant man-made influences control the evolution of future geomorphic conditions along the IWW.

7.2 RESULTS

Predictions of future geomorphic conditions along the UMR and IWW for the year 2050 are presented in the following sections.

7.2.1 Upper Mississippi River

In this section, the influences on the various reaches of the UMR are described and the predictions of the expected aquatic areas in the year 2050 are made. To provide context for the discussion, a general description of the characteristics of the involved geomorphic reaches is made prior to the discussion of results for individual pools. For each pool, a series of six plots were developed to describe the relative and absolute change for each aquatic class between historic, existing, and predicted future conditions. The plots are presented in Appendix F. A specific example of the plots is shown in Figure 7-1 for Pool 9.

Areas of concentrated changes, both historic and predicted, and associated geomorphic processes within the 23 pools along the UMR are shown on the maps in Appendix F. An example of these maps, showing the predicted future condition of Pool 20, is shown in Figure 7-2. A comparison of the geomorphic processes that have acted on the pools along the UMR historically and that are expected in the future is shown in Table 7-1. Overall, the summary shows a slight decrease in the number of locations experiencing significant deposition between historic and future conditions.

Tabular summaries of the predicted future aquatic areas along the UMR, excluding the Open River reaches, are presented pool by pool in Table 7-2, reach by reach in Table 7-3 and for the whole system in Table 7-4. A graphical summary of changes be aquatic class, by reach, is shown in Figure 7-3.

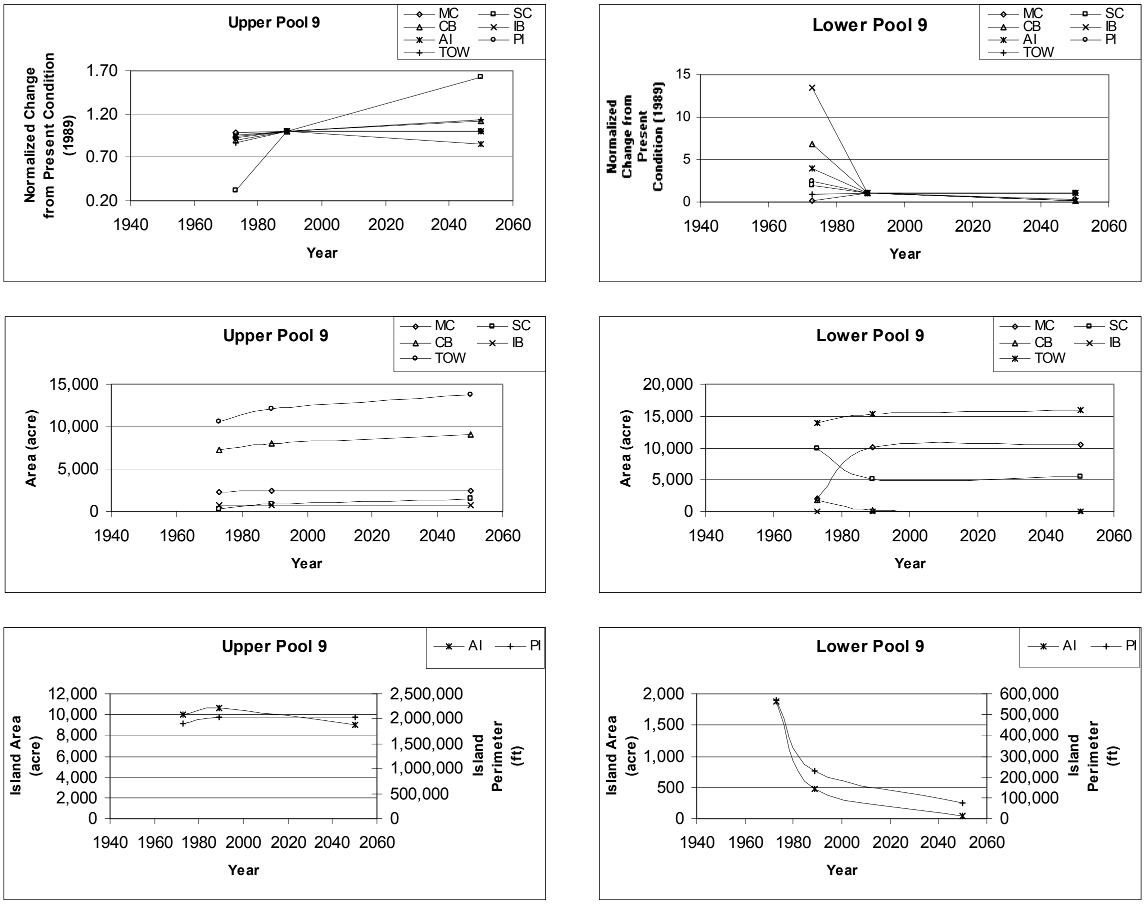


Figure 7-1: Plots of future geomorphic condition statistics for Pool 9. Plots for other pools are shown in Appendix F.

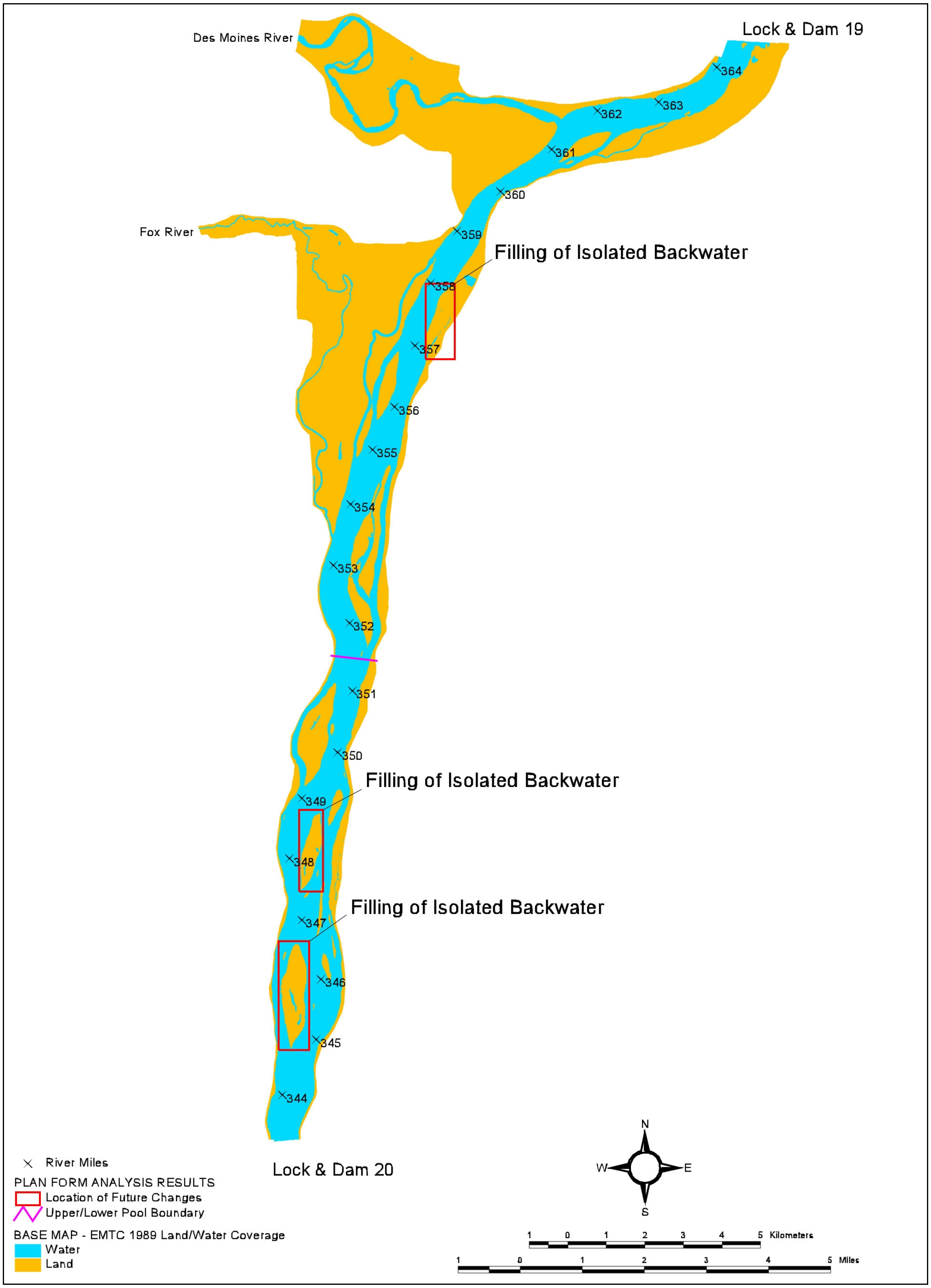


Figure 7-2: An example of maps showing predicted future geomorphic conditions. Full sized figures for every pool along the UMR are shown in Appendix F.

7.2.1.1 Geomorphic Reach 1

This reach encompasses the portion of the UMR study area upstream of Lake Pepin. It includes Pools 1 through 3. Historical plan form data and cross sectional data for the pools were either unavailable or extremely limited. Consequently, historical plan form analyses, cross sectional analyses, and sediment budget analyses could not be conducted for the involved pools. Therefore, no estimates of future geomorphic conditions were developed for the pools in Reach 1.

7.2.1.2 Geomorphic Reach 2

This reach is comprised only of Pool 4. The pool was defined as a separate geomorphic reach due to its unique geomorphic characteristics. The geomorphic conditions in the reach are related to the dominance of the alluvial fan of the Chippewa River and Lake Pepin.

Pool 4

The Chippewa River delta controls Lake Pepin and the geomorphic characteristics of the pool. Deltas have formed in the pool as a result of both upstream Mississippi River and tributary sediment supplies. The deltas can be expected to continue to prograde. Delta growth into contiguous backwater areas will lead to their reduction. Contiguous backwater areas at the upstream end of the pool can be expected to continuously form and fill as the delta in that area evolves.

Historically, channel maintenance dredging in lower Pool 4 was conducted at 5 or 6 dredge cuts downstream of the Chippewa River. Since the fall of 1984, a sediment trap has been maintained at the mouth of the Chippewa River to manage dredging in lower Pool 4. Available data (Rose, 1992; Personal communications with Hendrickson, 1998) indicate that the bed load sediment supply from the Chippewa River is reduced by 20 to 40 percent by the operation of the sediment trap. This reduction in bed load sediment supply has likely slowed the growth of the Big Lake delta. In addition, the total dredging volume and confined disposal of dredged material in lower Pool 4 probably affects the geomorphic conditions in downstream pools. However, annual dredging volumes in lower Pool 4 (which is equal to the total dredging in the pool) since 1984 are similar to what would be expected even if the trap had not been constructed. Hence, the sediment trap has moved the dredging from the main channel to the mouth of Chippewa River but the total volume dredged in the pool has remained approximately constant.

7.2.1.3 Geomorphic Reach 3

This reach involves Pools 5 through 9. All the pools in the reach are highly influenced by the large bed load sediment supply of the Chippewa River, which joins the UMR near the downstream limit of Pool 4. Prior to the construction of the UMR locks and dams system, the reach exhibited classic island-braided channel morphology.

Overall, the aquatic areas of the pools in the reach display a high level of complexity. Many of the pools have large open water areas as a result of water impoundment. The pools also have the largest areas of secondary channels, contiguous and isolated backwaters, islands, and number of islands measured along the UMR. For many of the pools in the reach, erosion of the islands in the lower portion of the pools has occurred since impoundment and the rate seems to have increased over the last 20 years in several of the pools. The island erosion is attributed to reduced bed load sediment supplies from the Chippewa River; general better land use practices; reservoir construction on the tributaries and wave action.

Pool 5

Upstream bed load sediment supply from the Chippewa River has been substantially reduced as is discussed in Section 7.2.1.2. Consequently, the number and area of islands in the pool has decreased. The erosion of islands may also increase fetch lengths that in turn can lead to increased wave action and erosion. This process is expected to continue.

It is noted that significant future change in the lower pool is not likely. Currently, almost the entire lower pool is open water area. Consequently, the aquatic classes in the lower pool have little opportunity to change.

In the upper pool, although historic data show a small increase in the area of secondary channels, a decrease is predicted for the future. This is expected since wind-wave erosion will likely convert existing secondary channel area into contiguous backwater area. The number of islands in the upper pool has increased significantly over time. This is due to the dissection and erosion of the islands. The perimeter of the islands has actually increased over time because of the erosion. However, a further increase in the perimeter of the islands is not predicted since island erosion is finite.

Pool 5A

Reduced upstream bed material sediment supply has altered the maintenance and growth of islands in the pool. This influence is expected to lead to increased contiguous backwater areas and reduced growth of island area throughout the upper pool. In the lower pool, decreases in the area of islands are expected due to wind wave erosion. The wind-wave erosion process is self-aggravating. As fetch lengths increase, erosion potential also increases. The erosion of islands is expected to result in the enlargement of other aquatic areas such as contiguous backwaters.

Pool 6

Overall changes in the aquatic areas within the pool have been and are expected to continue to be small. Historically, the area of islands of the pool has increased. It is expected that due to the reduction in upstream bed load supply, the area of islands will not increase. Accordingly, the perimeter of islands will not change. Measured and predicted small increases in backwater areas contradict common perceptions that major losses of these areas are occurring everywhere in the UMR system.

Pool 7
The geomorphic processes and human influences at work in Lake Onalaska are significant and complex. Reductions in bed load sediment supply to the pool have altered the balance between aggradation and degradation. Furthermore, human activities, such as dredging in the vicinity of Rosebud Island, has lead to the increase of secondary channel area and the creation of man-made islands has influenced wind-fetch through the lake.

In the lower pool, a significant delta has formed from a secondary channel coming from the main channel into Lake Onalaska. The delta growth is depicted in sequence of photos in Section 5.5.5.6. The delta was observed to prograde extensively over a 17-year historic period (1973 to 1989). The building of the delta has increased the area of islands and reduced other aquatic areas. Changes in the bed load supply to the delta will strongly influence whether it progrades or degrades. The bed load supply could be influenced by the installation of control structures at the head of the delta, dredging in the main channel and upstream sediment traps. It is predicted that growth of the delta will continue, but at a reduced rate, due to previously noted reductions in upstream bed load sediment supply.

The reduction in bed load supply is also expected to influence the formation or maintenance of islands in the upper pool. The slight historic increase in island area in the upper pool is expected to be counteracted by wind-wave erosion, resulting in no overall future change.

Pool 8
Geomorphic processes that are expected in Pool 8 include island dissection in the upper pool and wind-wave erosion of islands in the lower pool. The most significant changes are restricted to the lower pool. Of the various pools in the UMR, this pool experienced one of the greatest increases in water area due to the locks and dams construction. Historic data indicate that prior to locks and dams construction, channel and floodplain gradients began to flatten at the lower end of present Pool 8 in response to hydraulic constrictions caused by the Wisconsin River alluvial fan and downstream valley narrowing associated with the river entering a narrower gorge.

In the lower pool, erosion of islands has occurred since construction of the locks and dams. The wave erosion is depicted in photo sequence in Section 5.5.5.4 and the area reduction is plotted in Figure 5-49. As the islands erode away, the fetch length across the pool increases, leading to increased erosion potential. It is expected that almost all island area within the lower pool will be lost.

In general, little overall change in aquatic areas has occurred in the upper portion of Pool 8. However, islands in the upper pool have been dissected, and this is expected to continue. The perimeter of islands in the upper pool was observed to increase as islands dissected. This trend is expected to reverse as islands are eroded away completely.

Pool 9
In many respects, Pool 9 is similar to Pool 8. The pre-locks and dams gradients for the river and floodplain in present Pool 9 flattened as they approached the Wisconsin River

alluvial fan (Figure 5-2). As expected, it also experienced one of the greatest increases in water area due to locks and dams construction.

The trends of change for aquatic areas in Pools 8 and 9 are very similar. Erosion of islands occurred in the lower pool historically, and is expected to continue. The majority of the remaining islands in the lower pool are expected to be lost to wind-wave erosion.

The pattern of wind-wave erosion in the lower pool is expected to extend into the upper pool. This will result in reduced island area. Accordingly, an increase in the total water area is predicted in the upper pool.

7.2.1.4 Geomorphic Reach 4

Reach 4 includes Pools 10 through 13. The river valley walls within this reach are dominated by highly erosion resistant dolomite formations. These formations influence the ability of the river to adjust its location and aquatic areas. Generally, Reach 4 represents a transition between the complex aquatic areas seen in the pools of Reach 3 to much simpler channel form in downstream reaches.

Pool 10

The Wisconsin River entering Pool 10 is the most significant bed load sediment supply to join the Mississippi River between the Chippewa River in Pool 4 and Lock and Dam 10. The confluence of this tributary with the mainstem has historically influenced the form of the river. Upstream of the confluence, the river slope is flattened by the river's alluvial fan. At the Wisconsin River fan and slightly downstream the river becomes steeper and narrower due to the constricting effects of the fan and to the steeper valley slope on the downstream side of the fan. The dominance of the valley walls by very erosionally resistant carbonate rock formations downstream of the fan constricts the valley width and further enhances the magnitude of the downstream gradient on the alluvial fan. In fact, the overall width of the river valley narrows from upstream to downstream of the confluence.

In the upper pool, upstream of the Wisconsin River, contiguous and isolated backwater areas were observed to be diminishing historically. Generally, this trend is expected to continue. However, as contiguous backwater area is lost a slight increase in isolated backwater area is expected. The area of islands in the upper pool has increased from the mid-1970s. A continuing increase in the area of islands is not predicted. Since backwater areas are filling, it is expected that enlarging islands would ultimately accrete to form terrestrial floodplain surfaces.

In the lower pool, a small increase in total water area has occurred historically. This trend is expected to continue. Only small changes in other aquatic areas of the lower pool are expected. The narrow valley gorge associated with resistant dolomite formations downstream of the Wisconsin River confines the lower pool width and will prevent any significant change to the aquatic area in the lower pool.

Pool 11
Several tributaries influence Pool 11. The Grant, Platte, Little Maquoketa, and Turkey Rivers provide large inputs of suspended sediment from the surrounding hilly landscape that is underlain with easily eroded soils developed in thick deposits of loess. In addition, large inputs of bed load sediment are contributed from the Turkey River and from the Wisconsin River via Pool 10. Deltas are noted to have formed at the mouth of both the Grant River and Little Makoqueta River. The growth of the Grant River delta is depicted by photo sequence in Section 5.5.5.5. Growth of the deltas is expected to continue in the lower pool. Similarly, the bed load of the Turkey River is expected to continue the formation and building of islands in the uppermost portion of the lower pool and influence conditions in downstream pools. However, the perimeter of islands is not predicted to increase since existing small islands are expected to join, thereby decreasing the overall complexity of the islands and their associated perimeters.

In the upper pool, the sediment supplies from upstream sources and the Turkey River are expected to continue the trend of filling backwater areas. Although, the historic data for contiguous backwater areas in the upper pool fluctuates between trends for increase and decrease, the overall trend for the period of record is for a decrease in area. It is noted that sedimentation of backwater areas will influence contiguous backwater areas, secondary channels, and isolated backwaters.

Since the impoundment, the deposition in the main channel of lower Pool 11 has been significant as is discussed in Section 5.4.4. The deposition has been of same magnitude as the bed load input to Pools 10 and 11 from Wisconsin and Turkey Rivers. This has however not led to increased dredging in the lower pool, as the main channel is still sufficiently deep. However, over the next 50 years it is expected that the sedimentation will lead to dredging in the lower pool as it becomes shallower. It is also possible, as the main channel storage decreases, the channel will become more efficient and will flush some of the bed load to downstream pools, possibly leading to more dredging in these pools.

Pool 12
Overall, changes are predicted to be small within Pool 12. One localized area of change involving the loss of contiguous backwater was observed and is predicted to continue in the upper pool. The noted area of backwater loss is located immediately downstream of Lock and Dam 11. The construction of the dam likely reduced flow velocities through the area, increasing the potential for sediment deposition from main channel overflows.

In the lower pool, minor areas of island formation were noted in the uppermost part of the lower pool. Examples of the island formations are depicted in a sequence of photos in Section 5.5.5.7. The noted island formation is not predicted to continue in the future. As observed in the historic data, the trend of island formation decreased significantly in recent years. Wind-wave erosion is expected in the lowermost portion of the lower pool. The wind-wave erosion indicates that sediment supplies have decreased. This conclusion is in agreement with the prediction that island formation in the upper pool will not continue.

The relative stability of Pool 12 is attributed to its location within a relatively narrow bedrock gorge formed in erosionally resistant dolomite rock formations. Although localized erosion and sedimentation may occur within the pool, the surrounding bedrock prevents significant geomorphic change within the pool. Little future change is expected.

Pool 13

Overall, there have been small changes in the aquatic areas in Pool 13 based on the available plan form data with the exception of about 33% loss of backwater in the upper pool between 1975 and 1989. Accordingly, small changes are expected in the future, and no areas of concentrated change are predicted. It is noted that Pool 13 experienced one of the largest increases in total water area due to locks and dams construction. This is probably due to number of conditions related to changing geologic factors that control the morphology of the valley in this pool. These include the effects of regional and local bedrock structure that result in valley walls being developed in rock of weaker erosional resistance than were characteristic of the narrow gorge in Pools 10, 11, and 12, and to the interception of the modern valley by segments of ancient buried valley systems in the lower pool. Both factors contribute to significant expansions in valley width. Furthermore, this is a relatively long pool and the combined effects of its length with these wide valley segments account for the large increase in total water area after the locks and dams closure.

7.2.1.5 Geomorphic Reach 5

Reach 5 involves Pools 14 through 17. A significant portion of Pool 14 and all of Pool 15 occupy a relatively steep narrow bedrock gorge which greatly limits areas of contiguous and isolated backwater and numbers of islands. Downstream, in Pool 16, the valley gradient flattens and the valley width expands as the modern valley occupies a segment of an ancient river system. Islands become more numerous here, probably in response to flow expansion and velocity reduction that contribute to deposition of sediment transported through Pool 15. Farther downstream in Pool 17, the Mississippi River enters the ancient pre-glacial Iowa River valley where the valley width becomes exceptionally wide. The wide floodplain promotes flow expansion, velocity reduction, and contributes to extensive island development here. Reach 5 continues the trend of downstream decreasing complexity of aquatic areas that was noted previously. Areas of contiguous and isolated backwater and the total number of islands decrease significantly from Reach 5 downstream..

Pool 14
A loss of contiguous backwater was observed from historic data. This trend is predicted to occur throughout the upper pool. The loss of contiguous backwater area in the upper pool is probably due to the existence of a geologic control in the lower pool. The geologic control is seen to flatten the slope of the river in the upper pool. The reduction in slope results in the deposition of sediment and loss of backwater areas. However, it is important to note that the absolute change in total water area is small. Although a loss of 25 percent in backwater areas in upper Pool 14 is predicted, the absolute change in total water acreage is small. A large decrease in perimeter of islands is expected as their shape simplify as the contiguous backwaters fill in.

The lower pool is controlled by the geology of the area. The river enters the Fulton to Rock Island gorge in the lower pool. Consequently, there is little diversity in the aquatic areas of the lower pool. Almost all of the water area within the lower pool is classified as main channel. Therefore, little change can occur in the future within the lower pool.

Pool 15
This pool is contained within a rock gorge. The geologic control provided by erosion resistant bedrock results in overall uniform conditions throughout the pool. Therefore, the area of backwaters within the pool is small. No significant changes in the aquatic areas are predicted.

Pool 16
Overall, the magnitude of change in Pool 16 is small. No concentrated areas of change in aquatic areas are predicted to occur in Pool 16. One localized area of contiguous backwater loss was identified from the analysis of historic plan form data. Pool 16 also is confined within a bedrock gorge, but the valley width is considerably wider than the Fulton-to-Rock Island sector in Pools 14 and 15. The greater width and various orientations of ancient buried bedrock valley systems in the area suggests that the Pool 16 bedrock gorge has greater antiquity than the gorge in Pools 14 and 15.

Pool 17
In total the size of aquatic area changes that were observed in Pool 17 are small. Similarly, the predicted future changes are also minor and no areas of concentrated change are expected. The small amount of isolated backwater area in the pool has been decreasing steadily since impoundment by the Lock and Dam. Although the percentage change in isolated backwater area over time has been large, the area this change represents is small.

From the historical data, one area was observed along the reach where sedimentation between wing dams was occurring. Upstream of this pool, this process was not observed in the historical plan form data set. However, it is believed that numerous wing dams have been buried by sediment deposited within upstream pools although this process was not specifically observed. The filling of sediments between wing dams could be the result of either natural deposition or placement of dredged materials or both. Most wing dams along the UMR were constructed prior to the installation of the existing locks and dams system and it is likely that sediment deposition between wing dams began immediately following their construction. The long term effect of the wing dams has been concentration of flow, narrowing of the channel and deposition of sediment within the channel border areas.

7.2.1.6 Geomorphic Reach 6

Reach 6 involves Pools 18 and 19. Prior to the construction of locks and dams this reach, where it passed through the Fort Madison to Keokuk Rock Gorge, was among the steepest in the UMR system. It encompasses the Fort Madison to Keokuk Rock Gorge. Accordingly, the lift at Lock and Dam 19 is the highest and Pool 19 is the longest along the UMR. Due to the relatively narrow valley width of Pool 19, the relatively high dam, and the large sediment loads contributed to Reach 6 by the Iowa and Skunk Rivers, there has been considerable sedimentation in Pool 19 since lock and dam construction in 1913. The characteristics of the geology and structures in the reach make its geomorphic conditions unique along the UMR.

Pool 18

Several related processes were observed in Pool 18. In the upper pool, steady loss of backwater areas has been occurring. This trend is expected to continue. Deposition is located downstream of the confluence with the Iowa River, a large sediment source. Historical filling between wing dams is also observed and is depicted in a photo sequence in Section 5.5.5.3.

In the lower pool, both island formation and wind-wave erosion of islands were observed in the historical data. It is expected that island formation will continue in the future considering the available sediment supply from the Iowa River and the historical trend from the plan form data. The area of wind-wave erosion is small and therefore wind-wave erosion is expected to be insignificant in the future.

Pool 19

Pool 19 is unique due to its size and age. Lock and Dam 19 was constructed in 1913, much earlier than the other locks and dams in the system. With the exception of Lock and Dam 1, all other locks and dams were constructed in the 1930s. The lift of the lock is 38 ft, which is the highest on the UMR. A hydroelectric power plant is also located at the dam. This high dam created a unique situation for sediment deposition in the pool, as the storage volume created by the dam is the largest in the UMR system.

Results of the sediment budget show that Pool 19 accumulated about 10 times the amount of sediment that other pools collected prior to the 1950s. Consequently, comparison of conditions within Pool 19 to other pools along the UMR is generally not valid. The causes of sediment deposition in the pool are related to the operation and physical characteristics of the dam. The operation of Pool 19 is significantly different than all other locks and dams on the UMR. The other locks and dams operate as open river for a small percentage of each year. During open river operation all gates at the dam are fully open and no regulation of the flow occurs. However, at Lock and Dam 19, the only time it has had all its gates open was during the great flood of 1993. In fact, opening of the gates at that time, was found to be very difficult due to the sediment accumulation at the gates (Personal communications with C. Beckert, 1998).

The Skunk River, a significant sediment source to the UMR, enters the upper pool. A significant and steady loss of backwater areas was identified in the upper pool from historic plan form data. Close to half of the backwater areas were determined to have been lost over the periods of analysis. A photo sequence depicting the loss of backwater area and filling of isolated backwater, in a portion of upper Pool 19, is shown in Section 5.5.5.1. It is predicted that such loss of backwater areas will continue in the future.

In the lower pool, no concentrated areas of plan form change were observed from the historical data. Absolute values of all aquatic areas, other than the main channel, are small. Overall, the lower pool is not expected to exhibit significant plan form change in the future.

7.2.1.7 Geomorphic Reach 7

Reach 7 is comprised of Pools 20 through 22. As seen from historic maps and aerial photographs, the reach exhibits evidence of old meander belts and has extensive deposits of post-glacial alluvium. These phenomena indicate that lateral channel migrations and adjustments were a common natural process in this reach during post-glacial time, but during historic time the river has been largely artificially confined by training structures..

Pool 20

Overall, changes in aquatic areas of the pool are small. Historic plan form data analysis results indicate the loss of various small areas of contiguous backwaters and the filling of sediment between wing dams. It is noted that area of contiguous and isolated backwaters is small. The percentage change of isolated backwater areas is a reflection of their small size.

The Des Moines River, a major tributary to the UMR and source of bedload sediment, joins Pool 20 in the upper pool. Backwater areas downstream of the confluence were found to be filling with sediments and are predicted to continue to do so. The filling between wing dams is judged to have been substantially completed. No significant future filling between wing dams is predicted as the aerial photos show that most of the areas between the wing dams are filled in.

Pool 21

The geomorphic changes, observed in Pool 21, are very similar to those observed for Pool 20. Backwater areas were observed to be decreasing over the historic period of record. This change is most significant in the upper portion of the pool. This trend is expected to continue. Areas between wing dams were also observed to be filling at several locations over the period of record. Future filling between wing dams is expected.

Pool 22
The results for Pool 22 are similar to those for the other pools within Reach 7. The overall change in aquatic areas within the pool is small. Results of the analysis of historic plan form data indicate increase of contiguous backwaters. However, the total open water area has historically decreased by a similar amount. It is expected that sedimentation in backwater areas will reverse the increasing trend for contiguous and isolated backwaters. The loss is expected primarily within the upper pool.

7.2.1.8 Geomorphic Reach 8

Reach 8 includes Pools 24 through 26. The profile of the reach has been historically influenced by the alluvial fans of the Illinois and Missouri Rivers. The alluvial fan complex has produced a hump in the longitudinal profile of the UMR, and is responsible for a pronounced flattening of hydraulic and thalweg profiles in Pools 25 and 26 (Figure 5-2 and Figure 5-57). Similar to Reach 7, evidence of post-glacial meander belts and extensive deposits of post-glacial alluvium are observed in historic plan form data. As in Reach 7, these meander scars and alluvial deposits of post-glacial age, are evidence that the UMR has experienced relatively large lateral adjustments in this reach during post-glacial time, but historic changes have been very minor. Generally, the complexity of aquatic areas appears to be somewhat greater in Reach 8 than Reach 7.

Pool 24
The extrapolation of future conditions for Pool 24 are hampered by the lack of historic data since the construction of the locks and dams. However, the trend of change can be inferred by comparison of 1989 data to 1930 pre-dam data. This is considered possible because the change between pre- and post-dam conditions is small. Hence, small future changes are expected. The only historic concentrated change noted in the pool was the filling of sediment between wing dams. A single location of concentrated loss of contiguous backwater area is predicted for the future.

It is observed that Pool 24 is influenced by the confluence of the Salt River, a significant sediment load contributor to the UMR. In addition, the profile of the UMR in Pool 24 begins to be influenced by the alluvial fan of the Illinois River. Although the Lock and Dam 24 is about 56 miles upstream of the Illinois River the thalweg profile (Figure 5-57) is observed to be flattening. The average thalweg slope in the reach is less than 0.5 ft/mile so a build up of an alluvial fan over geological time of about 30 ft would create backwater effects about 60 miles upstream. The combination of a significant tributary sediment supply and a flattening river profile would be expected to increase sediment deposition within the pool. Available historic dredging information support this conclusion, average annual dredging volumes in Pool 24 are and have always been significantly larger than in the pools immediately upstream.

Pool 25
Historic data for Pool 25 was also limited. However, comparison of pre-locks and dams conditions to 1989 conditions revealed slight overall change in aquatic areas. Similar to

Pool 24, it is expected that the observed loss of backwater area and filling between wing dams will continue.

Also similar to Pool 24, the profile of Pool 25 is influenced by the downstream alluvial fan complex of the Illinois River and Missouri River. The reduction in slope caused by the fan likely impacts the hydraulics of flow and sediment transport of the reach. Historic dredging information for the pool indicate that dredging volumes increase significantly in Pool 25 compared to upstream pools.

Pool 26

The historic data for Pool 26 indicates that backwater areas have decreased somewhat. This trend is expected to continue. Areas between wing dams were also noted to have filled over the historic period of record. It is predicted that backwater areas will fill at a rate similar to the historic trend. Overall, the relative change in aquatic area within the pool is small.

The Illinois River joins the pool about midway along its length. The influence of the Illinois River alluvial fan is observable on thalweg elevation profiles of the UMR. The thalweg slope upstream of the confluence can almost be characterized as adverse. The slope influences the hydraulics of flow and associated sediment transport. Evaluation of historic dredging data reveals that dredging activities are concentrated just upstream of the confluence. The records show no dredging has occurred in the pool downstream of the confluence. This reflects the influence of the confluence on the deposition of sediment. The amount of dredging in Pool 26 is greater than almost any other pool in the UMR.

It is also noted that the Missouri River joins the UMR about 8 miles downstream of Lock and Dam 26. The alluvial fan of the Missouri River also influences the slope of the upstream UMR, the hydraulic conditions within Pool 26, and the evolution of aquatic areas within upstream pools.

7.2.1.9 Geomorphic Reaches 9 and 10

Geomorphic Reaches 9 and 10 are referred to as the Open River section of the UMR. No locks and dams are located along these reaches. Reach 9 encompasses the section of the river from below Lock and Dam 26 to Thebes Gap (River Miles 202 to 45). Reach 10 extends from the rock gorge at Thebes Gap to the confluence with the Ohio River, near Cairo, Illinois (River Miles 45 to 0).

The upper portion of Reach 9 is highly influenced by the alluvial fan of the Missouri River. Sediment supplies from the Missouri River have been reduced from historic levels by the construction of upstream mainstem reservoirs (USACE, 1981). However, the magnitude of the suspended sediment supply from the Missouri River is still much larger than the suspended sediment supply of the UMR upstream of their confluence.

Compared to upstream reaches of the UMR, the aquatic areas of the Open River reaches have relatively little complexity. The reaches are primarily limited to two aquatic classes, main channel, and secondary channels. As seen in Appendix F, the contiguous and isolated backwater areas along the reaches are quite small. In fact, most of the contiguous backwater area is associated with secondary channels that have been purposely blocked. A large number of wing dams are located along the reaches. It is also noted that the river is closely confined within levees, railroad embankments and bluff lines along both banks.

A previous study of the Open River (Simons et al, 1974) concluded that the position of the river is basically unchanged in the last 200 years and, in the absence of earthquakes or great floods, should remain so. Except for major secondary channels, natural side channels in the reach are being filled with sediment. Ultimately, most natural and man-induced side channels are expected to fill with sediment and become indistinguishable from the floodplain. In addition, small secondary channels can be expected to fill faster than large secondary channels.

One of the products from the Simons et al. (1974) study were maps of river bank lines for the years 1880 and 1968. The maps of historic bank lines are useful for the general identification of changes associated with main channel and secondary channel aquatic areas. Other aquatic areas cannot be distinguished from the maps. The number of secondary channels determined from the data for the years 1880 and 1968, are 35 and 27, respectively. A total of 25 secondary channels were identified from the 1989 WES Hydraulic Classification GIS coverage. It is noted that 10 of the 25 secondary channels were blocked by engineering structures as seen in the 1989 GIS coverage. The observed blockages could not be discerned from the 1968 data. Including the 10 blocked channels, the data imply a rate of decrease of number of secondary channels for both time periods to be about one secondary channel per decade. Therefore, these results indicate that the rate of decrease in the number of secondary channels today is similar to what it has been over the last 100 years.

An evaluation was also conducted to identify general changes in main channel location for the post-locks and dams era along the Open River reaches. This was accomplished by overlaying 1980s era land/water boundary information (EMTC, 1998) on the 1968 bank line data. The developed overlay is presented in Appendix G. The overlay indicates almost no change in the main channel location over the this time period represented. A detailed discussion is provided in Section 5.5.4.

Craig (Personal communications with M. Craig, 1998) investigated changes in individual secondary channels. Plan form changes identified over the period of 1950 to 1994 for five out of six secondary channels investigated show a substantial decrease in aquatic area (see Figure 5-43). In most cases, the decrease in secondary channel area is more than 50 percent over the roughly 45-year period. Only one of the secondary channels investigated appeared to be relatively stable.

In general, the conditions of the Open River reaches in the Year 2050 are expected to be similar to existing conditions, with the exception that a significant percentage of secondary channels and related backwater areas will be filled with sediment. By extrapolation of the estimated rate of loss for secondary channels, approximately 6 of the remaining 25 secondary channels along the reach will be lost. However, this result is highly dependent on future river management decisions.

According to Craig's data (Personal communications with M. Craig, 1998), the rate of decrease in the area of the remaining secondary channels is slowing (See Figure 5-42). The area of the remaining secondary channels is expected to decrease by at least 40 percent by the year 2050. Again, river management decisions will highly influence this result. As previously concluded by Simons et al. (1974), the decreases will affect smaller chute (secondary) channels first and large chute channels last.

7.2.2 Summary for Upper Mississippi River

Table 7-1 summarizes the concentrated areas of observed and predicted geomorphic processes in each pool. The involved areas of change are plotted on the maps presented in Appendix F. Reach 3 (Pools 5-9) has been and is predicted to continue to be dominated by island erosion. Reaches 4 through 10 (Pools 10 – Open River) have all experienced loss of contiguous backwater, especially reaches 6 through 10 (Pools 18 – Open River) where loss of isolated backwater has also been occurring. Generally, both of these processes are expected to continue for these reaches. Filling between wing dams has been historically observed in Reaches 6-10 (Pools 18 – Open River) but is not expected to continue except in limited cases. In most instances, the areas between wing dams have already filled and little additional filling can occur. The total number of concentrated areas of historic geomorphic change is 47 whereas the predicted number of concentrated areas of change is 39 which is a slight decrease. This represents a slight decrease in the expected geomorphic changes and is mostly related to predicted reduction in the filling of sediment between wing dams.

In Figure 7-3 a bar chart is presented summarizing the percent change expected for each aquatic class from present (1989) to 2050. Reach 3 (Pools 5-9) is the only reach where water area is expected to increase, including both isolated and contiguous backwater. This is due to the predicted continued erosion of islands in the reach. In all other reaches, total water area is expected to decrease, including both isolated and contiguous backwater areas.

In Table 7-2 the absolute changes predicted for each aquatic class in each pool are presented. In Table 7-3 the absolute and percent of change predicted in each aquatic class are summarized for each geomorphic reach defined along the UMR. A summary of the total absolute and percent change predicted for all the pools along the UMR is presented in Table 7-4. As seen from Table 7-4, total water area is predicted to decrease by 1.4 percent by the year 2050, with the major part of that decrease in the upper portion of the pools. Backwater areas are predicted to decrease by a slightly greater percentage. Again, the major decrease is expected in the upper portions of the pools. The area of the main channel is expected to decrease by less than 1 percent, while secondary channels are expected to decrease by about 2.6 percent. The area of islands is expected to decrease overall by 2.0 percent largely due to the island erosion predicted to occur in Reach 3. For many other reaches, the area of islands actually increases. Overall, the total perimeter of islands is predicted to decrease by 3.7%.

When evaluating the results presented in Table 7-2 to Table 7-4 it is important to note the variability in the percentage change associated with each aquatic class, lower and upper portion of individual pools, and total pool. Erroneous conclusions can be drawn from the summary data if appropriate consideration is not given to the resolution of the data and the associated statistics. Furthermore, the absolute value of an aquatic class area should be considered in evaluating the significance of the calculated relative percentage change. A slight change in a small absolute value will result in a deceptively large relative change. For example, in Pool 16 the area of isolated backwater is predicted to decrease by 89 percent and the main channel area to increase by 8 percent. Although the predicted percent loss for the isolated backwater is much larger than the predicted increase in main channel area, the predicted area increase for the main channel is almost four times larger than the predicted decrease in isolated backwater area.

Table 7-1: Historic and predicted future dominant geomorphic processes along the UMR. The light gray represents historic changes and black represents future changes.

Geomorphic Reach	Pool	Loss of Contiguous Backwater		Filling of Isolated Backwaters		Loss of Secondary Channels		Filling between Wing Dams		Wind-Wave Erosion of Islands		Island Dissection		Tributary Delta Formation		Delta Formation		Island Formation	
		Historic	Future	Historic	Future	Historic	Future	Historic	Future	Historic	Future	Historic	Future	Historic	Future	Historic	Future	Historic	Future
2	4	░	■											░	■	░	■		
3	5									░	■								
	5A									░	■								
	6																		
	7									░	■	░	■			░	■		
	8									░	■	░	■						
	9									░	■								
4	10	░	■																
	11	░	■											░	■			░	■
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	13																		
5	14	░	■																
	15																		
	16	░																	
	17							░											
6	18	░	■		■			░		░								░	■
	19	░	■											░	■				
7	20	░			■			░											
	21	░	■					░											
	22	░	■		■														
8	24	░			■	░	■	░											
	25	░			■			░	■										
	26	░	■		■			░											
9	OR	░	■	░	■	░	■	░											
10	OR	░	■	░	■	░	■	░											

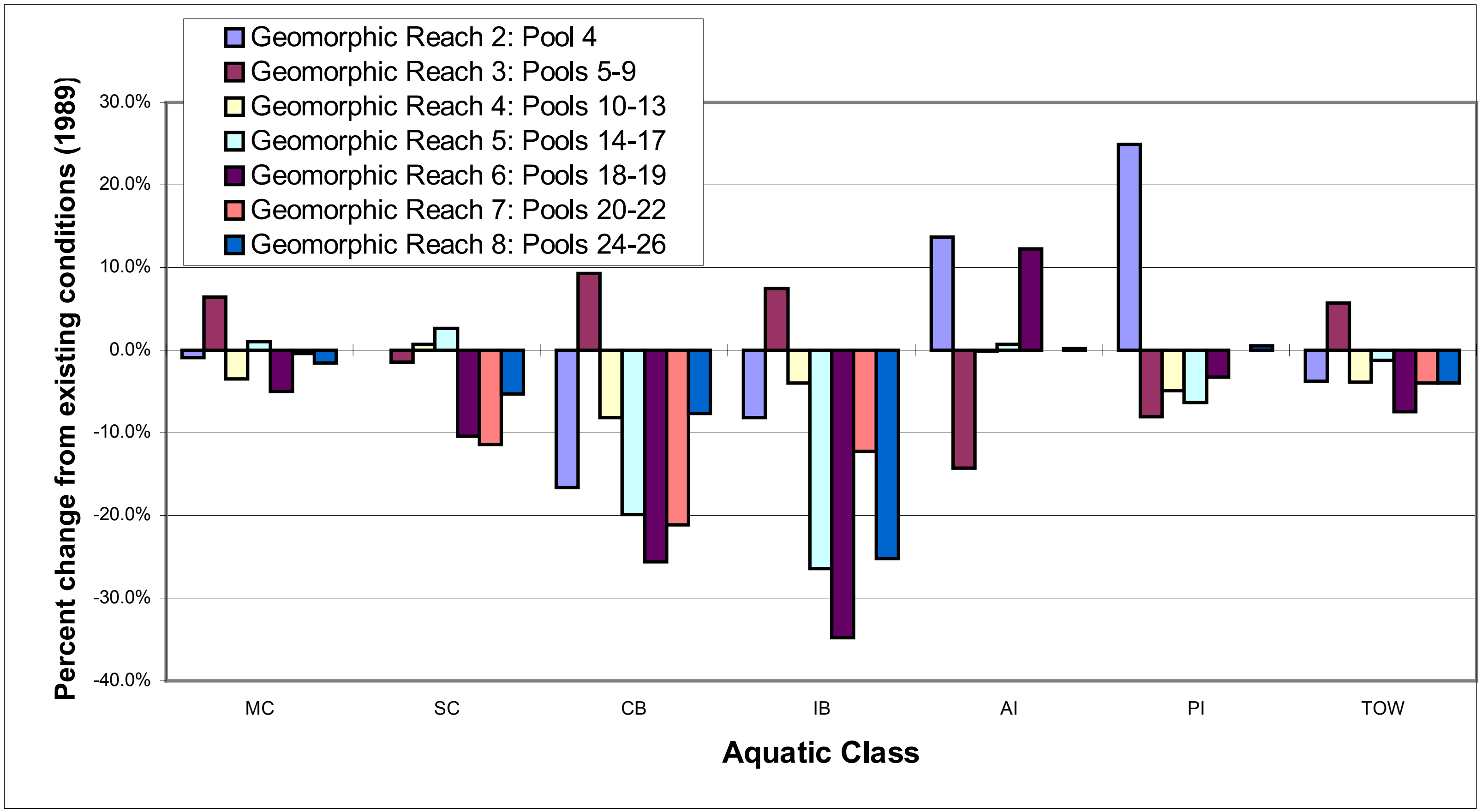

Figure 7-3: Predicted percent change within each geomorphic reach from present conditions (1989) to the year 2050.

Table 7-2: Summary of predicted geomorphic changes within UMR by Pool.

Pool 4		MC	SC	CB	IB	AI	PI	TOW
Predictions for 2050		acre	acre	acre	acre	acre	ft	acre
Lower Pool	1989	2,230	659	4,054	189	3,718	768,400	7,132
River Miles	2050	2,230	659	3,446	180	4,462	998,920	6,515
764.7 - 752.8	% Change	0%	0%	-15%	-5%	20%	30%	-9%
Upper Pool	1989	23,600	1,323	2,066	384	1,726	158,200	27,373
River Miles	2050	23,364	1,323	1,653	346	1,726	158,200	26,686
796.9 - 764.7	% Change	-1%	0%	-20%	-10%	0%	0%	-3%
Total Pool	1989	25,830	1,982	6,120	573	5,444	926,600	34,505
River Miles	2050	25,594	1,982	5,099	526	6,188	1,157,120	33,201
796.9 - 752.8	% Change	-1%	0%	-17%	-8%	14%	25%	-4%

Pool 5		MC	SC	CB	IB	AI	PI	TOW
Predictions for 2050		acre	acre	acre	acre	acre	ft	acre
Lower Pool	1989	1,927	860	82	0	43	28,300	2,869
River Miles	2050	2,040	860	8	0	4	8,949	2,908
743.1 - 738.1	% Change	6%	0%	-90%	0%	-91%	-68%	1%
Upper Pool	1989	1,221	1,294	4,377	452	2,234	692,500	7,344
River Miles	2050	1,470	934	5,559	452	1,626	588,625	8,415
752.8 - 743.1	% Change	20%	-28%	27%	0%	-27%	-15%	15%
Total Pool	1989	3,148	2,154	4,459	452	2,277	720,800	10,213
River Miles	2050	3,510	1,794	5,567	452	1,630	597,574	11,323
752.8 - 738.1	% Change	11%	-17%	25%	0%	-28%	-17%	11%

Pool 5A		MC	SC	CB	IB	AI	PI	TOW
Predictions for 2050		acre	acre	acre	acre	acre	ft	acre
Lower Pool	1989	396	682	922	31	596	204,600	2,031
River Miles	2050	396	614	1,041	28	477	182,094	2,079
732.8 - 728.3	% Change	0%	-10%	13%	-10%	-20%	-11%	2%
Upper Pool	1989	839	391	1,889	472	3,620	673,350	3,591
River Miles	2050	923	391	2,229	472	4,272	731,445	4,015
738.1 - 732.8	% Change	10%	0%	18%	0%	18%	9%	12%
Total Pool	1989	1,235	1,073	2,811	503	4,216	877,950	5,622
River Miles	2050	1,319	1,005	3,270	500	4,749	913,539	6,094
738.1 - 728.3	% Change	7%	-6%	16%	-1%	13%	4%	8%

MC = Main Channel; SC = Secondary Channel; CB = Contiguous Backwater;
IB = Isolated backwater; AI = Area of Islands; PI = Perimeter of Islands;
TOW = Total Open Water Area.

Table continued on following page.

Table continued from previous page.

Pool 6		**MC**	**SC**	**CB**	**IB**	**AI**	**PI**	**TOW**
Predictions for 2050		acre	acre	acre	acre	acre	ft	acre
Lower Pool	1989	1,704	1,050	644	3,030	1,022	382,050	6,428
River Miles	2050	1,874	1,050	708	3,333	1,022	382,050	6,965
723.9 - 714.2	% Change	10%	0%	10%	10%	0%	0%	8%
Upper Pool	1989	612	278	548	847	661	180,800	2,285
River Miles	2050	673	334	603	932	661	180,800	2,542
728.3 - 723.9	% Change	10%	20%	10%	10%	0%	0%	11%
Total Pool	1989	2,316	1,328	1,192	3,877	1,683	562,850	8,713
River Miles	2050	2,547	1,384	1,311	4,265	1,683	562,850	9,507
728.3 - 714.2	% Change	10%	4%	10%	10%	0%	0%	9%

Pool 7		**MC**	**SC**	**CB**	**IB**	**AI**	**PI**	**TOW**
Predictions for 2050		acre	acre	acre	acre	acre	ft	acre
Lower Pool	1989	881	6,542	984	49	1,888	356,200	8,456
River Miles	2050	969	6,210	1,033	49	2,171	381,134	8,261
706.8 - 702.5	% Change	10%	-5%	5%	0%	15%	7%	-2%
Upper Pool	1989	1,481	410	2,122	160	2,107	570,000	4,173
River Miles	2050	1,481	369	2,228	192	2,107	570,000	4,270
714.2 - 706.8	% Change	0%	-10%	5%	20%	0%	0%	2%
Total Pool	1989	2,362	6,952	3,106	209	3,995	926,200	12,629
River Miles	2050	2,450	6,579	3,261	241	4,278	951,134	12,531
714.2 - 702.5	% Change	4%	-5%	5%	15%	7%	3%	-1%

Pool 8		**MC**	**SC**	**CB**	**IB**	**AI**	**PI**	**TOW**
Predictions for 2050		acre	acre	acre	acre	acre	ft	acre
Lower Pool	1989	7,554	519	4,134	18	777	307,400	12,225
River Miles	2050	8,293	52	4,406	18	233	168,370	12,769
689.9 - 679.1	% Change	10%	-90%	7%	0%	-70%	-45%	4%
Upper Pool	1989	1,875	1,175	4,339	637	6,657	1,189,700	8,026
River Miles	2050	2,025	1,175	4,122	701	4,660	999,348	8,023
702.5 - 689.9	% Change	8%	0%	-5%	10%	-30%	-16%	0%
Total Pool	1989	9,429	1,694	8,473	655	7,434	1,497,100	20,251
River Miles	2050	10,318	1,227	8,528	719	4,893	1,167,718	20,792
702.5 - 679.1	% Change	9%	-28%	1%	10%	-34%	-22%	3%

Pool 9		**MC**	**SC**	**CB**	**IB**	**AI**	**PI**	**TOW**
Predictions for 2050		acre	acre	acre	acre	acre	ft	acre
Lower Pool	1989	10,081	5,067	281	3	474	231,850	15,432
River Miles	2050	10,421	5,407	28	3	47	74,192	15,859
660.0 - 647.9	% Change	3%	7%	-90%	0%	-90%	-68%	3%
Upper Pool	1989	2,390	943	7,722	779	10,655	2,037,921	11,834
River Miles	2050	2,390	1,535	9,057	779	9,057	2,037,921	13,761
679.1 - 660.0	% Change	0%	63%	17%	0%	-15%	0%	16%
Total Pool	1989	12,471	6,010	8,003	782	11,129	2,269,771	27,266
River Miles	2050	12,811	6,942	9,085	782	9,104	2,112,113	29,620
679.1- 647.9	% Change	3%	16%	14%	0%	-18%	-7%	9%

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Pool 10		MC	SC	CB	IB	AI	PI	TOW
Predictions for 2050		acre	acre	acre	acre	acre	ft	acre
Lower Pool	1989	1,726	1,859	1,915	167	1,556	565,300	5,667
River Miles	2050	1,847	1,989	2,215	217	1,245	503,117	6,268
624.8 - 615.1	% Change	7%	7%	16%	30%	-20%	-11%	11%
Upper Pool	1989	3,832	2,129	3,233	521	8,854	1,162,100	9,715
River Miles	2050	4,100	2,278	1,617	594	8,854	1,045,890	8,589
647.9 - 624.8	% Change	7%	7%	-50%	14%	0%	-10%	-12%
Total Pool	1989	5,558	3,988	5,148	688	10,410	1,727,400	15,382
River Miles	2050	5,947	4,267	3,832	811	10,099	1,549,007	14,857
647.9 - 615.1	% Change	7%	7%	-26%	18%	-3%	-10%	-3%

Pool 11		MC	SC	CB	IB	AI	PI	TOW
Predictions for 2050		acre	acre	acre	acre	acre	ft	acre
Lower Pool	1989	9,866	777	2,554	67	1,006	308,500	13,264
River Miles	2050	7,893	777	3,065	67	1,257	308,500	11,802
599.0 - 583.0	% Change	-20%	0%	20%	0%	25%	0%	-11%
Upper Pool	1989	2,411	1,264	1,836	263	3,431	556,700	5,774
River Miles	2050	2,411	1,071	1,469	210	3,240	528,865	5,161
615.1 - 599.0	% Change	0%	-15%	-20%	-20%	-6%	-5%	-11%
Total Pool	1989	12,277	2,041	4,390	330	4,437	865,200	19,037
River Miles	2050	10,304	1,848	4,534	277	4,497	837,365	16,963
615.1 - 583.0	% Change	-16%	-9%	3%	-16%	1%	-3%	-11%

Pool 12		MC	SC	CB	IB	AI	PI	TOW
Predictions for 2050		acre	acre	acre	acre	acre	ft	acre
Lower Pool	1989	1,405	1,835	945	29	1,124	283,800	4,214
River Miles	2050	1,700	1,835	800	25	972	283,800	4,360
563.5 - 556.7	% Change	21%	0%	-15%	-14%	-14%	0%	3%
Upper Pool	1989	3,443	1,385	1,620	272	3,072	631,900	6,720
River Miles	2050	3,443	1,385	1,620	272	3,072	631,900	6,720
583.0 - 563.5	% Change	0%	0%	0%	0%	0%	0%	0%
Total Pool	1989	4,848	3,220	2,565	301	4,196	915,700	10,934
River Miles	2050	5,143	3,220	2,420	297	4,044	915,700	11,080
583.0 - 556.7	% Change	6%	0%	-6%	-1%	-4%	0%	1%

Pool 13		MC	SC	CB	IB	AI	PI	TOW
Predictions for 2050		acre	acre	acre	acre	acre	ft	acre
Lower Pool	1989	12,781	1,873	4,179	540	3,671	634,400	19,373
River Miles	2050	12,781	1,873	4,179	432	4,038	634,400	19,265
545.8 - 522.5	% Change	0%	0%	0%	-20%	10%	0%	-1%
Upper Pool	1989	2,080	326	620	508	626	102,900	3,534
River Miles	2050	2,080	326	558	457	626	102,900	3,421
556.7 - 545.8	% Change	0%	0%	-10%	-10%	0%	0%	-3%
Total Pool	1989	14,861	2,199	4,799	1,048	4,297	737,300	22,907
River Miles	2050	14,861	2,199	4,737	889	4,664	737,300	22,686
556.7 - 522.5	% Change	0%	0%	-1%	-15%	9%	0%	-1%

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Pool 14		MC	SC	CB	IB	AI	PI	TOW
Predictions for 2050		acre	acre	acre	acre	acre	ft	acre
Lower Pool	1989	2,854	77	45	19	54	13,700	2,995
River Miles	2050	2,854	77	45	19	54	13,700	2,995
502.8 - 493.3	% Change	0%	0%	0%	0%	0%	0%	0%
Upper Pool	1989	3,743	1,319	1,329	235	3,354	418,850	6,626
River Miles	2050	3,743	1,319	1,000	176	3,354	281,795	6,238
522.5 - 502.8	% Change	0%	0%	-25%	-25%	0%	-33%	-6%
Total Pool	1989	6,597	1,396	1,374	254	3,408	432,550	9,621
River Miles	2050	6,597	1,396	1,045	195	3,408	295,495	9,233
522.5 - 493.3	% Change	0%	0%	-24%	-23%	0%	-32%	-4%

Pool 15		MC	SC	CB	IB	AI	PI	TOW
Predictions for 2050		acre	acre	acre	acre	acre	ft	acre
Lower Pool	1989	1,333	165	61	6	953	49,700	1,565
River Miles	2050	1,333	165	61	6	953	49,700	1,565
488.2 - 482.9	% Change	0%	0%	0%	0%	0%	0%	0%
Upper Pool	1989	1,672	233	23	10	306	26,700	1,938
River Miles	2050	1,672	233	23	10	306	26,700	1,938
493.3 - 488.2	% Change	0%	0%	0%	0%	0%	0%	0%
Total Pool	1989	3,005	398	84	16	1,259	76,400	3,503
River Miles	2050	3,005	398	84	16	1,259	76,400	3,503
493.3 - 482.9	% Change	0%	0%	0%	0%	0%	0%	0%

Pool 16		MC	SC	CB	IB	AI	PI	TOW
Predictions for 2050		acre	acre	acre	acre	acre	ft	acre
Lower Pool	1989	2,515	2,419	718	56	1,991	400,700	5,708
River Miles	2050	2,707	2,685	574	6	1,991	440,770	5,972
468.4 - 457.2	% Change	8%	11%	-20%	-89%	0%	10%	5%
Upper Pool	1989	3,272	1,386	255	369	1,442	187,600	5,282
River Miles	2050	3,272	1,386	117	332	1,442	187,600	5,107
482.9 - 468.4	% Change	0%	0%	-54%	-10%	0%	0%	-3%
Total Pool	1989	5,787	3,805	973	425	3,433	588,300	10,990
River Miles	2050	5,979	4,071	691	338	3,433	628,370	11,079
482.9 - 457.2	% Change	3%	7%	-29%	-20%	0%	7%	1%

Pool 17		MC	SC	CB	IB	AI	PI	TOW
Predictions for 2050		acre	acre	acre	acre	acre	ft	acre
Lower Pool	1989	1,864	932	512	50	1,660	221,100	3,358
River Miles	2050	1,864	863	512	5	1,660	221,100	3,244
446.0 - 437.1	% Change	0%	-7%	0%	-90%	0%	0%	-3%
Upper Pool	1989	2,063	962	95	9	1,262	142,150	3,129
River Miles	2050	2,063	962	95	1	1,339	146,350	3,121
457.2 - 446.0	% Change	0%	0%	0%	-89%	6%	3%	0%
Total Pool	1989	3,927	1,894	607	59	2,922	363,250	6,487
River Miles	2050	3,927	1,825	607	6	2,999	367,450	6,365
457.2 - 437.1	% Change	0%	-4%	0%	-90%	3%	1%	-2%

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Pool 18		MC	SC	CB	IB	AI	PI	TOW
Predictions for 2050		acre	acre	acre	acre	acre	ft	acre
Lower Pool	1989	3,819	24	162	3	243	71,950	4,008
River Miles	2050	3,704	24	162	3	386	90,657	3,893
418.0 - 410.5	% Change	-3%	0%	0%	0%	59%	26%	-3%
Upper Pool	1989	4,104	1,910	905	164	4,804	628,850	7,083
River Miles	2050	3,858	1,910	499	126	4,948	638,213	6,393
437.1 - 418.0	% Change	-6%	0%	-45%	-23%	3%	1%	-10%
Total Pool	1989	7,923	1,934	1,067	167	5,047	700,800	11,091
River Miles	2050	7,562	1,934	661	129	5,334	728,870	10,286
437.1 - 410.5	% Change	-5%	0%	-38%	-23%	6%	4%	-7%

Pool 19		MC	SC	CB	IB	AI	PI	TOW
Predictions for 2050		acre	acre	acre	acre	acre	ft	acre
Lower Pool	1989	14,263	0	889	109	25	12,600	15,261
River Miles	2050	14,263	0	889	109	3	1,260	15,261
384.0 - 364.2	% Change	0%	0%	0%	0%	-88%	-90%	0%
Upper Pool	1989	8,153	3,249	605	106	6,170	588,500	12,113
River Miles	2050	6,988	2,710	355	11	7,281	529,650	10,064
410.5 - 384.0	% Change	-14%	-17%	-41%	-90%	18%	-10%	-17%
Total Pool	1989	22,416	3,249	1,494	215	6,195	601,100	27,374
River Miles	2050	21,251	2,710	1,244	120	7,284	530,910	25,325
410.5 - 364.2	% Change	-5%	-17%	-17%	-44%	18%	-12%	-7%

Pool 20		MC	SC	CB	IB	AI	PI	TOW
Predictions for 2050		acre	acre	acre	acre	acre	ft	acre
Lower Pool	1989	2,113	943	10	13	927	88,000	3,079
River Miles	2050	2,113	943	10	7	927	88,000	3,073
351.3 - 343.2	% Change	0%	0%	0%	-46%	0%	0%	0%
Upper Pool	1989	3,543	459	89	26	980	124,900	4,117
River Miles	2050	3,543	404	89	20	980	124,900	4,056
364.2 - 351.3	% Change	0%	-12%	0%	-23%	0%	0%	-1%
Total Pool	1989	5,656	1,402	99	39	1,907	212,900	7,196
River Miles	2050	5,656	1,347	99	27	1,907	212,900	7,129
364.2 - 343.2	% Change	0%	-4%	0%	-31%	0%	0%	-1%

Pool 21		MC	SC	CB	IB	AI	PI	TOW
Predictions for 2050		acre	acre	acre	acre	acre	ft	acre
Lower Pool	1989	1,923	40	658	24	338	56,500	2,645
River Miles	2050	1,923	40	632	23	338	56,500	2,618
331.2 - 324.9	% Change	0%	0%	-4%	-4%	0%	0%	-1%
Upper Pool	1989	2,475	1,614	226	158	5,856	299,100	4,473
River Miles	2050	2,401	1,291	26	148	5,856	299,100	3,866
343.2 - 331.2	% Change	-3%	-20%	-88%	-6%	0%	0%	-14%
Total Pool	1989	4,398	1,654	884	182	6,194	355,600	7,118
River Miles	2050	4,324	1,331	658	171	6,194	355,600	6,484
343.2 - 324.9	% Change	-2%	-20%	-26%	-6%	0%	0%	-9%

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Pool 22		MC	SC	CB	IB	AI	PI	TOW
Predictions for 2050		acre	acre	acre	acre	acre	ft	acre
Lower Pool	1989	2,466	425	135	26	294	76,700	3,052
River Miles	2050	2,466	425	122	23	294	76,700	3,036
309.2 - 301.2	% Change	0%	0%	-10%	-12%	0%	0%	-1%
Upper Pool	1989	3,607	610	205	56	1,630	168,200	4,478
River Miles	2050	3,607	519	164	45	1,630	168,200	4,335
324.9 - 309.2	% Change	0%	-15%	-20%	-20%	0%	0%	-3%
Total Pool	1989	6,073	1,035	340	82	1,924	244,900	7,530
River Miles	2050	6,073	944	286	68	1,924	244,900	7,371
324.9 - 301.2	% Change	0%	-9%	-16%	-17%	0%	0%	-2%

Pool 24		MC	SC	CB	IB	AI	PI	TOW
Predictions for 2050		acre	acre	acre	acre	acre	ft	acre
Lower Pool	1989	2,322	1,440	323	76	766	174,750	4,161
River Miles	2050	2,299	1,411	307	72	728	178,245	4,089
282.1 - 273.4	% Change	-1%	-2%	-5%	-5%	-5%	2%	-2%
Upper Pool	1989	4,098	1,667	340	348	3,089	269,200	6,453
River Miles	2050	4,016	1,634	323	331	3,027	266,508	6,304
301.2 - 282.1	% Change	-2%	-2%	-5%	-5%	-2%	-1%	-2%
Total Pool	1989	6,420	3,107	663	424	3,855	443,950	10,614
River Miles	2050	6,315	3,045	630	403	3,755	444,753	10,393
301.2 - 273.4	% Change	-2%	-2%	-5%	-5%	-3%	0%	-2%

Pool 25		MC	SC	CB	IB	AI	PI	TOW
Predictions for 2050		acre	acre	acre	acre	acre	ft	acre
Lower Pool	1989	3,415	548	1,721	60	1,373	306,160	5,744
River Miles	2050	3,347	537	1,687	57	1,400	309,222	5,628
251.0 - 241.5	% Change	-2%	-2%	-2%	-5%	2%	1%	-2%
Upper Pool	1989	5,278	2,869	423	399	5,638	464,300	8,969
River Miles	2050	5,172	2,811	415	379	5,751	468,943	8,777
273.4 - 251.0	% Change	-2%	-2%	-2%	-5%	2%	1%	-2%
Total Pool	1989	8,693	3,417	2,144	459	7,011	770,460	14,713
River Miles	2050	8,519	3,348	2,102	436	7,151	778,165	14,405
273.4 - 241.5	% Change	-2%	-2%	-2%	-5%	2%	1%	-2%

Pool 26		MC	SC	CB	IB	AI	PI	TOW
Predictions for 2050		acre	acre	acre	acre	acre	ft	acre
Lower Pool	1989	5,422	894	1,038	305	1,118	208,000	7,659
River Miles	2050	5,422	894	830	162	1,118	208,000	7,308
217.6 - 202.9	% Change	0%	0%	-20%	-47%	0%	0%	-5%
Upper Pool	1989	5,245	2,695	402	514	5,268	385,500	8,856
River Miles	2050	5,140	2,291	362	272	5,268	385,500	8,065
241.5 - 217.6	% Change	-2%	-15%	-10%	-47%	0%	0%	-9%
Total Pool	1989	10,667	3,589	1,440	819	6,386	593,500	16,515
River Miles	2050	10,562	3,185	1,192	434	6,386	593,500	15,373
241.5 - 202.9	% Change	-1%	-11%	-17%	-47%	0%	0%	-7%

Table 7-3: Summary of predicted geomorphic changes within UMR by Geomorphic Reach.

Geom. R. 2: Pool 4		**MC**	**SC**	**CB**	**IB**	**AI**	**PI**	**TOW**
Predictions for 2050		acre	acre	acre	acre	acre	ft	acre
Lower Pool	1989	2,230	659	4,054	189	3,718	768,400	7,132
	2050	2,230	659	3,446	180	4,462	998,920	6,515
	% Change	0.0%	0.0%	-15.0%	-4.8%	20.0%	30.0%	-8.7%
Upper Pool	1989	23,600	1,323	2,066	384	1,726	158,200	27,373
	2050	23,364	1,323	1,653	346	1,726	158,200	26,686
	% Change	-1.0%	0.0%	-20.0%	-9.9%	0.0%	0.0%	-2.5%
Total Pool	1989	25,830	1,982	6,120	573	5,444	926,600	34,505
	2050	25,594	1,982	5,099	526	6,188	1,157,120	33,201
	% Change	-0.9%	0.0%	-16.7%	-8.2%	13.7%	24.9%	-3.8%

Geom. R. 3: Pools 5-9		**MC**	**SC**	**CB**	**IB**	**AI**	**PI**	**TOW**
Predictions for 2050		acre	acre	acre	acre	acre	ft	acre
Lower Pool	1989	22,543	14,720	7,047	3,131	4,800	1,510,400	47,441
	2050	23,993	14,193	7,224	3,431	3,954	1,196,789	48,841
	% Change	6.4%	-3.6%	2.5%	9.6%	-17.6%	-20.8%	3.0%
Upper Pool	1989	8,418	4,491	20,997	3,347	25,934	5,344,271	37,253
	2050	8,962	4,738	23,798	3,528	22,383	5,108,139	41,026
	% Change	6.5%	5.5%	13.3%	5.4%	-13.7%	-4.4%	10.1%
Total Pool	1989	30,961	19,211	28,044	6,478	30,734	6,854,671	84,694
	2050	32,955	18,931	31,022	6,959	26,337	6,304,928	89,867
	% Change	6.4%	-1.5%	10.6%	7.4%	-14.3%	-8.0%	6.1%

Geom. R. 4: Pools 10-13		**MC**	**SC**	**CB**	**IB**	**AI**	**PI**	**TOW**
Predictions for 2050		acre	acre	acre	acre	acre	ft	acre
Lower Pool	1989	25,778	6,344	9,593	803	7,357	1,792,000	42,518
	2050	24,221	6,474	10,259	741	7,512	1,729,817	41,695
	% Change	-6.0%	2.0%	6.9%	-7.7%	2.1%	-3.5%	-1.9%
Upper Pool	1989	11,766	5,104	7,309	1,564	15,983	2,453,600	25,743
	2050	12,034	5,060	5,264	1,533	15,792	2,309,555	23,891
	% Change	2.3%	-0.9%	-28.0%	-2.0%	-1.2%	-5.9%	-7.2%
Total Pool	1989	37,544	11,448	16,902	2,367	23,340	4,245,600	68,260
	2050	36,255	11,534	15,523	2,274	23,304	4,039,372	65,586
	% Change	-3.4%	0.8%	-8.2%	-3.9%	-0.2%	-4.9%	-3.9%

Geom. R. 5: Pools 14-17		**MC**	**SC**	**CB**	**IB**	**AI**	**PI**	**TOW**
Predictions for 2050		acre	acre	acre	acre	acre	ft	acre
Lower Pool	1989	8,566	3,593	1,336	131	4,658	685,200	13,626
	2050	8,758	3,790	1,192	36	4,658	725,270	13,776
	% Change	2.2%	5.5%	-10.8%	-72.5%	0.0%	5.8%	1.1%
Upper Pool	1989	10,750	3,900	1,702	623	6,364	775,300	16,975
	2050	10,750	3,900	1,235	519	6,441	642,445	16,404
	% Change	0.0%	0.0%	-27.4%	-16.7%	1.2%	-17.1%	-3.4%
Total Pool	1989	19,316	7,493	3,038	754	11,022	1,460,500	30,601
	2050	19,508	7,690	2,427	555	11,099	1,367,715	30,180
	% Change	1.0%	2.6%	-20.1%	-26.4%	0.7%	-6.4%	-1.4%

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Geom. R. 6: Pools 18-19		MC	SC	CB	IB	AI	PI	TOW
Predictions for 2050		acre	acre	acre	acre	acre	ft	acre
Lower Pool	1989	18,082	24	1,051	112	268	84,550	19,269
	2050	17,967	24	1,051	112	389	91,917	19,154
	% Change	-0.6%	0.0%	0.0%	0.0%	45.1%	8.7%	-0.6%
Upper Pool	1989	12,257	5,159	1,510	270	10,974	1,217,350	19,196
	2050	10,846	4,620	854	137	12,229	1,167,863	16,457
	% Change	-11.5%	-10.4%	-43.4%	-49.3%	11.4%	-4.1%	-14.3%
Total Pool	1989	30,339	5,183	2,561	382	11,242	1,301,900	38,465
	2050	28,813	4,644	1,905	249	12,618	1,259,780	35,611
	% Change	-5.0%	-10.4%	-25.6%	-34.8%	12.2%	-3.2%	-7.4%

Geom. R. 7: Pools 20-22		MC	SC	CB	IB	AI	PI	TOW
Predictions for 2050		acre	acre	acre	acre	acre	ft	acre
Lower Pool	1989	6,502	1,408	803	63	1,559	221,200	8,776
	2050	6,502	1,408	764	53	1,559	221,200	8,727
	% Change	0.0%	0.0%	-4.9%	-15.9%	0.0%	0.0%	-0.6%
Upper Pool	1989	9,625	2,683	520	240	8,466	592,200	13,068
	2050	9,551	2,214	279	213	8,466	592,200	12,257
	% Change	-0.8%	-17.5%	-46.3%	-11.3%	0.0%	0.0%	-6.2%
Total Pool	1989	16,127	4,091	1,323	303	10,025	813,400	21,844
	2050	16,053	3,622	1,043	266	10,025	813,400	20,984
	% Change	-0.5%	-11.5%	-21.2%	-12.2%	0.0%	0.0%	-3.9%

Geom. R. 8: Pools 24-26		MC	SC	CB	IB	AI	PI	TOW
Predictions for 2050		acre	acre	acre	acre	acre	ft	acre
Lower Pool	1989	11,159	2,882	3,082	441	3,257	688,910	17,564
	2050	11,068	2,842	2,824	291	3,246	695,467	17,025
	% Change	-0.8%	-1.4%	-8.4%	-34.0%	-0.3%	1.0%	-3.1%
Upper Pool	1989	14,621	7,231	1,165	1,261	13,995	1,119,000	24,278
	2050	14,328	6,736	1,100	982	14,046	1,120,951	23,146
	% Change	-2.0%	-6.8%	-5.6%	-22.1%	0.4%	0.2%	-4.7%
Total Pool	1989	25,780	10,113	4,247	1,702	17,252	1,807,910	41,842
	2050	25,396	9,578	3,924	1,273	17,292	1,816,418	40,171
	% Change	-1.5%	-5.3%	-7.6%	-25.2%	0.2%	0.5%	-4.0%

MC = Main Channel; SC = Secondary Channel; CB = Contiguous Backwater;
IB = Isolated backwater; AI = Area of Islands; PI = Perimeter of Islands;
TOW = Total Open Water Area.

Table 7-4: Summary of predicted geomorphic changes within UMR.

Pools 4 - 26 Predictions for 2050		MC	SC	CB	IB	AI	PI	TOW
		acre	acre	acre	acre	acre	ft	acre
Lower Pool	1989	94,860	29,630	26,966	4,870	25,617	5,750,660	156,326
River Miles	2050	94,739	29,390	26,760	4,844	25,780	5,659,380	155,733
796.9 - 202.9	% Change	-0.1%	-0.8%	-0.8%	-0.5%	0.6%	-1.6%	-0.4%
Upper Pool	1989	91,037	29,891	35,269	7,689	83,442	11,659,921	163,886
River Miles	2050	89,835	28,591	34,183	7,258	81,083	11,099,353	159,867
796.9 - 202.9	% Change	-1.3%	-4.3%	-3.1%	-5.6%	-2.8%	-4.8%	-2.5%
Total Pool	1989	185,897	59,521	62,235	12,559	109,059	17,410,581	320,211
River Miles	2050	184,574	57,981	60,943	12,102	106,863	16,758,733	315,600
796.9 - 202.9	% Change	-0.7%	-2.6%	-2.1%	-3.6%	-2.0%	-3.7%	-1.4%

MC = Main Channel; SC = Secondary Channel; CB = Contiguous Backwater;
IB = Isolated backwater; AI = Area of Islands; PI = Perimeter of Islands;
TOW = Total Open Water Area.

7.2.3 Illinois Waterway

The glacial history of the UMR valley strongly influences the existing and future geomorphic conditions of the IWW. Until the Mississippi River was diverted by runoff from glacial ice about 20,000 years ago the course of the river extended southeastward across northern Illinois and then into the present course of the Illinois River at the head of Reach 2. The anomalous deep, wide valley and relatively flat gradient for Reach 2 of the IWW is accounted for in large part by its being the course of the ancient Mississippi River. Since deglaciation of the region, sediments eroded from steep tributaries have built large alluvial fans and deltas into Reach 2 of the IWW river valley causing the formation of natural constrictions, lakes, and backwaters. The much steeper longitudinal gradient of upstream Reach 1 of the IWW was developed on local areas of bedrock, but mainly on glacial deposits of the most recent glaciation of the region. Reach 1 has a very steep gradient which accounts for the close spacing of locks and dams there. .

As defined by its geologic history, the IWW is characteristically low gradient, aggradational, and has large backwater areas from its mouth to Starved Rock Lock and Dam (RM 231.0). The sedimentation occurring within this reach threatens to convert the backwater areas into marshes (Bhowmik, 1994). Upstream of the Starved Rock Lock and Dam, the IWW is significantly steeper and backwater areas are much less significant.

Comparisons were made of historic land/water boundaries along IWW. As seen in Appendix G, the land/water boundaries between the mouth and Brandon Lock and Dam (RM 286.0) in the 1980s (EMTC, 1998) were overlain on river mapping from the 1930s (Personal communications with C. Beckert, 1998). Generally, it was observed from the overlay comparison that the main channel of the IWW has not changed significantly since the 1930s, even in the downstream reaches of the IWW. This result is not surprising considering that the main channel is maintained for navigation. However, significant variability was noted in backwater areas along the channel. No detailed area measurements of the noted change in backwater areas were made as the resolution of the 1980s data set was insufficient since it was developed from 1:100,000 scale maps.

Numerous studies have been previously conducted to investigate the trend of sedimentation along the IWW and its backwater areas (Lee and Stall, 1976; Bellrose et al., 1983; Demissie and Bhowmik, 1986; Demissie et al, 1992). Lee and Stall (1976) concluded that backwater lake volume was being lost at an annual rate ranging from 0.6 to 1.1 percent over the period of 1903 to 1975. Bellrose et al. (1983) estimated that the number of years required for selected lakes to lose half their average depth under various sedimentation rates ranged from 24 to 127 years.

Demissie and Bhowmik (1986) conducted an investigation of the sedimentation characteristics of Peoria Lake, which is the largest and deepest lake on the IWW. Their comparison of limited historic cross sections for the lake demonstrated sediment accumulation depths of up to 14 feet in various locations of the lake and the navigation channel was relatively stable over the period of record. As of 1985, the lake was estimated to have lost up to 2/3 of its 1903 volume. The study concluded that if sedimentation continued at current rates, within 10 or 15 years the river and lake will reach dynamic equilibrium and net accumulation of sediment in the lake will be zero. Most of the area outside of the channel is predicted to become either a mud flat or marshy wetland area, depending on the ability of vegetation to grow in the lake sediment.

Currently, numerous studies are underway to address the sedimentation problem in Peoria Lake, including investigation of methods to remove existing sediment and decrease resuspension of sediment (Personal communications with C. Beckert, 1998).

Demissie et al. (1992) prepared an overall assessment of erosion and sedimentation in the IWW basin. It included a sediment budget for the IWW developed by comparing sediment input from tributaries to the mainstem gages at Valley City. The sediment budget showed that on average 8.2 million tons of sediment are deposited in the IWW valley each year. Major areas impacted by the sediment deposition are backwater lakes. An average capacity loss for the lakes of 72 percent was calculated. Sedimentation in the navigation channel was not considered to be as high as that of the backwater lakes. The higher flow velocities and tow traffic in the channel are said to keep the sediment moving in the channel. The study concluded that without management of sediment, all bottomland lakes along the IWW would eventually fill with sediment.

Overall, the future geomorphic conditions of the IWW are well defined. The geologic history of the IWW created conditions where sedimentation is and will continue to be the predominant geomorphic process. More sediment supplies from tributary areas are deposited within the IWW river valley than are transported through it. However, the rate at which sediments are supplied to the IWW and sedimentation occurs is undoubtedly influenced by human activities, such as land-use, water regulation, and dredging.

Most of the investigators of the IWW agree that significant sedimentation is occurring under current conditions and most backwater areas will be filled with fine sediment within the foreseeable future. According to Demissie and Bhowmik (1986), equilibrium between the sediment supply and transport out of Peoria Lake, the largest and deepest pool along the IWW, will be reached within the next few years. The navigation channel has not changed significantly in plan form over the period of record. Higher flow velocities and maintenance dredging along the channel effectively prevent significant change along its length.

In summary, according to previous studies, by the year 2050 the IWW is predicted to lose a significant portion of its off-main channel backwater areas under current conditions of sediment supply. The affected contiguous and isolated backwater areas are expected to convert to mud flats or marshy wetlands. The location and area of the main channel is expected to remain relatively the same with the exception that it will become more defined within the various pools along the IWW.

8 CONCLUSIONS AND RECOMMENDATIONS

In the preceding chapters, the methods and results of a detailed evaluation of the cumulative physical effects of the 9-ft Channel Project were presented. The evaluation included a review of pertinent prior studies, identification of controlling geomorphic characteristics, description of significant human influences, and characterization of historic changes along the UMR system. A wide range of existing literature and data were collected and reviewed. This included collection and review of historic discharge and sediment measurements records and analysis of existing 2-dimensional hydraulic models. Information on structures and dredging were collected and analyzed. Historic changes were determined from the identification, delineation, measurement, and analysis of approximately 25,000 plan form features and about 2,000 channel cross sections. Results of the analyses were used to predict future physical and ecological conditions along the UMR. An assessment of cumulative ecological effects is presented in Volume 2 of this report.

8.1 CONCLUSIONS

General conclusions of the study include the following:

- The UMR basin has a total drainage area of over 710,000 square miles and encompasses major portions of five states (Illinois, Iowa, Missouri, and Wisconsin).

- The watershed has a sub-humid to humid continental climate, characterized by cold, dry winters and warm to hot, moist summers. The average annual precipitation over the basin is about 32 inches. Floods along the UMR commonly occur as a result of snowmelt or a combination of rainfall and snowmelt.

- Agricultural is the primary land use. Cropland comprises almost 70 percent of land use in Illinois and Iowa. Anecdotal and quantitative measures indicate that improved land use practices have reduced historic watershed sediment yields to the UMR.

- Flow along the UMR is affected by numerous man-made and natural influences. These include levees, wing dams, bridges, channel erosion and sedimentation, dredging, locks and dams, dams and reservoirs on tributaries, watershed land use, consumptive water use, and potentially climate change.

- Long-term discharge records for the UMR at St. Paul, Minnesota, Clinton, Iowa, and Keokuk, Iowa indicate trends toward increasing runoff during the winter and increased occurrences of moderate to large floods overall. Minimum annual daily discharges at St. Louis have trended upward over time, which could be related to the operation of reservoirs in the basin. Increases are also noted in the mean annual discharge over time, which indicates an apparent increase in the total volume of runoff along the UMR, and may be evidence of climate change. In general, it can be concluded that man-made and natural influences have affected the maximum, average, and minimum discharge conditions along the UMR.

- River stages within the UMR navigation pools are significantly influenced by the operation of the 9-ft Channel Project locks and dams. The amount of influence is dependent on flow conditions and location within the navigation pool. Generally, low flow stages have increased and fluctuations in stage decreased due to the operation of the locks and dams in the downstream end of the pools. In Reaches 2 through 4, comparison between pre- and post-dam water surface profiles indicates a decrease in river stage in the upstream end of the pools. The decreased fluctuations of stage are most pronounced in the impoundment typically found in the lower third of each pool. The damping of stage fluctuations reduces in an upstream direction through the pool.

- The 9-ft Channel Project and levees have influenced river stages within the Open River portion of the UMR. The construction of wing dams, dredging of the navigation channel, placement of dredged materials within borders of the channel, and closure of secondary channels have narrowed and deepened the main channel of the UMR, reducing its bank full flow capacity. The construction of levees along the UMR has isolated large portions of the floodplain from the river and reduced available flood storage capacity.

- Recent studies suggest that global warming has been occurring in the Northern Hemisphere throughout the 20th century. It is expected that the warming trend will continue over the next 50 years. Changes in average global temperatures are expected to change patterns of atmospheric and oceanic circulation. These changes will, in turn, influence occurrences of floods and droughts. The type and intensity of precipitation in the UMR basin may be altered as a result. More intense rainfalls could increase watershed erosion and sediment supplies to the UMR. Increased rainfall during winter months could influence the pattern and magnitude of annual runoff and floods. Overall, future climatic and hydrologic conditions are probably not well represented by existing historic records.

- Construction of wing dams along the UMR began as early as the late 1800s. Hundreds of wing dams have been constructed along the route of the 9-ft Channel Project. Generally, wing dams concentrate flow in the navigation channel, induce sediment deposition within channel border areas, and control flow into secondary channels.

- The majority of locks and dams along the UMR and IWW were constructed in the 1930s. Lock and Dam 19 is the oldest structure within the study area. The location and lift at each lock and dam is generally determined by the natural gradient of the river, geologic controls that presented obstacles to navigation, and confluences with major tributaries. Generally, the gradient of the lower IWW is much flatter than the gradient of the UMR.

- A total of 266 reservoirs, having normal storage capacities of at least 5,000 acre-feet and maximum capacities of 25,000 acre-feet, have been constructed within the UMR basin. The pools of the 9-ft channel project represent about 13 percent of this total. The other 87 percent of the reservoirs are distributed throughout the basin and are located on most major tributaries to the UMR. About 80 percent of all the reservoirs were constructed during the post-locks and dams era (1930 to 1989) and about 40 percent of that amount were constructed during the period of 1930 to 1939. One impact of the construction of reservoirs is reflected in the decrease of suspended sediment load measured downstream of reservoirs in several locations in the basin. The decreased sediment load from tributaries has resulted in decreased sedimentation rates along the UMR and major reductions in historic dredging.

8.1.1 Upper Mississippi River

Conclusions of the study related to the UMR are presented in the following sections:

8.1.1.1 Geomorphology

Conclusions of the geomorphic analysis conducted for the study include:

- Successive periods of glaciation have eroded and deposited great masses of sediment in the UMR basin and have been responsible for many major adjustments in the direction and pattern of the river drainage. River diversions caused by glacial ice and geologic structures and rock strata of variable erosional resistance account for the large variability in valley morphology and river characteristics throughout the study area.

- Most of the UMR watershed beyond the limits of late Wisconsin age glacial deposits have surficial sediments of silt-dominated loess that is easily eroded. The loess deposits commonly range in thickness from 5 to 20 feet along the margins of the Mississippi River and up to 30 feet in east central Iowa.

- Ten reaches having unique geomorphic characteristics were identified along UMR within the study area. The reaches are defined as:

  Reach 1 – Pools 1 through 3
  Reach 2 – Pool 4 (Lake Pepin)
  Reach 3 – Pools 5 through 9
  Reach 4 – Pools 10 through 13
  Reach 5 – Pools 14 through 17
  Reach 6 – Pools 18 through 19
  Reach 7 – Pools 20 through 22
  Reach 8 – Pools 24 through 26
  Reach 9 – Below Pool 26 to Thebes Gap
  Reach 10 – Thebes Gap to Ohio River

- The physical characteristics of an individual pool can vary significantly compared to the other pools within the same geomorphic reach. Geologic controls, tributaries, levees, and locks and dams characteristics have influenced the plan form of individual pools.

- Maps of concentrated areas of historic geomorphic change were developed for each UMR pool (See Appendix E). As denoted on the maps, the areas of change were grouped into nine general categories of geomorphic processes. For several pools no concentrated areas of geomorphic change were defined. However, it is noted that the overall measured change for any individual aquatic class may still be significant.

- Generally, the complexity of aquatic areas within navigation pools is greatest among the pools in the upstream geomorphic reaches of the UMR. A general decrease in the complexity of aquatic areas occurs between Pools 10 and 15. The complexity of aquatic areas was found to be least along the Open River segment of the UMR.

- Both contiguous and isolated backwater areas decrease in a downstream direction along the river. Downstream of Pool 14, the number and area of these aquatic classes are much smaller than upstream.

- For the period from the mid-1970s to 1989, the total water area within Reach 3 (Pools 5 through 9) increased. A corresponding decrease in island area was also observed. This conclusion indicates a reversal in the trend for water area in these pools as compared to the conclusions of the GREAT I study, which was based on data from 1939 to 1973. The island erosion is attributed to a reduction in bed load sediment supply, off-channel disposal of dredged materials and wave action.

- Overall, Geomorphic Reaches 5 (Pools 14 through 17) and 7 (Pools 20 through 22) were found to be the most stable since the construction of locks and dams. The stability of these reaches is attributed to geologic control.

- Compared to pre-locks and dams conditions, the width of the main channel is narrower in the upstream part of almost every pool. The narrowing of the channel is attributed to the placement of dredged materials and natural sedimentation along the channel border. Conversely, the main channel width was found to be wider in the lower portion of most pools due to water impoundment caused by the locks and dams.

- Both the median size of islands and the median perimeter of islands increase from upstream to downstream.

- Plan form overlays developed for Pools 11, 14, 15, 19, and the Open River indicate that little overall change has occurred in the position of the UMR during the post-locks and dams era.

8.1.1.2 Sediment Transport

The following conclusions can be made regarding conditions of sediment transport along the UMR:

- Sediments along the UMR navigation channel are almost totally comprised of sand-sized or finer material (<2mm). Between the Des Moines River confluence in Pool

20 and Lock and Dam 26, up to gravel-sized material have also been measured. Sediments in the lower third of each pool, along the navigation channel, are typically finer than sediments in upstream portions of the pool. Sediments collected in the main channel, but outside of the navigation channel, in the lower third of each UMR pool are characteristically comprised of fine and very fine sand-sized material (0.0625 to 0.25 mm). Available data indicate that the mean size of sediments in backwater areas of the UMR is characteristically medium to fine sand-sized material.

- Low energy slopes in the pooled reach of the UMR limit suspended sediment transport capacity. Generally, only fine sediments (silts and clays) can be transported in suspension. Suspended sediment measurements indicate that sand-sized materials are primarily transported as bed load downstream of Pool 11.

- Average annual suspended sediment discharge between Anoka, Minnesota, and Thebes, Illinois, increases by a factor of about 618 along the UMR. The suspended load of the UMR increases by over a factor of 4 at the confluence with the Missouri River.

- Plots of available suspended sediment measurement records indicate significant variability. It is evident from the data that utilization of short measurement records may result in erroneous estimates of average suspended sediment load and similar periods of records should be employed in conducting sediment transport analyses.

- Long-term suspended sediment records for four mainstem measurement stations indicate a decreasing trend for the suspended sediment load along the UMR since the mid-1940s. The decrease is attributed to construction of numerous large reservoirs on most major tributaries to the UMR and to improved agricultural land use practices.

- Historic cross section data indicate that significant sedimentation occurred within the main channel of the UMR in Pools 11 through 22 during the first two decades after construction of locks and dams. The greatest amount of sedimentation occurred in Pool 19. About 10 times more sediment accumulated in Pool 19 compared to the amount of accumulation in the other pools.

- Analysis of available cross section data for the period from mid-1950s until present indicates that the main channel has degraded throughout the Rock Island District, with the exception of Pools 11 and 13. The rate of degradation is on the order of less than one centimeter per year.

- Results of the sediment budget analysis indicate that, system-wide, the average annual rate of sediment deposition in off-main channel areas is small at present, on the order of millimeters per year. Previous sedimentation rate estimates vary considerably, ranging from several centimeters per year to less than 0.5 centimeters per year. Results of the current study support lower estimates for current condition sedimentation rates. It is noted that sediment deposition rates for backwaters estimated through the sediment budget analysis reflect average conditions for all off-main channel areas. Localized sediment deposition rates can vary significantly from the average.

- Results from the sediment budget indicate that, for some reaches where dredging amounts are large, complete removal of dredge material from the system could decrease sedimentation in backwaters.

- The sediment budget indicates that tributary sediment loads have decreased by about 40 to 50 percent since construction of the 9-ft Channel Project. This is most likely due to construction of numerous large reservoirs on tributaries and improved land use management practices over time.

8.1.1.3 Dredging

Study conclusions related to historic dredging activities along the UMR include:

- The average amount of sediment dredged per year has decreased over time in every pool along the UMR. In some cases, the decrease has been by an order of magnitude. The decrease in dredging amounts is attributed to improved agricultural land use practices, construction of numerous large reservoirs on most major tributaries, improved sediment management practices resulting from environmental laws, changing dredging philosophies and economic considerations. A sediment trap was constructed near the mouth of the Chippewa River in lower Pool 4 in the 1980s that collects a large amount of bed load and has a local effect on geomorphology within lower Pool 4. Maintenance of the trap has not changed the total amount of sediment historically removed from Pool 4. The trap has not changed any impacts on downstream pools. However, the confined placement of dredged sediments in Pools 4 through 10 has effectively removed these sediments from the river environment. Only a small fraction of the dredged sediments reenter the river environment due to shoreline erosion of confined placement sites. The majority of the sediments is either moved out of the floodplain when placement sites are emptied, or is used beneficially within the floodplain (e.g. for island building) where they are stabilized so that they do not reenter the sediment transport system. The sediment transport capacity of the UMR main channel has increased by the concentration of flow in the main channel caused by wing dams, placement of the dredged material and natural sedimentation along the channel border, and slight overall degradation of the main channel.

- Currently, the greatest average annual amount of dredging along the UMR is in Pools 4, 24, 25, and 26.

- The average annual dredging requirements in most UMR pools is directly correlated to bed load sediment supply from tributaries. Recognition of this correlation is very important for dredging management along the UMR. Control of supply from certain tributaries could reduce dredging requirements and backwater sediment accumulation.

- Sedimentation in the main channel of lower Pool 11 has been large since impoundment, of similar magnitude as the bed load input to Pools 10 and 11 from the Wisconsin and Turkey Rivers. However, very little dredging has been required as the main channel in lower Pool 11 is still sufficiently deep. However, it could be expected that lower Pool 11 would require increased dredging over the next 50 years as the main channel becomes shallower. It is also likely, as the main channel sediment storage capacity decreases, the channel will become more efficient in flushing some of the bed load to downstream pools, possibly leading to more dredging in those pools.

- During the first 1 to 2 decades after the construction of locks and dams, intensive dredging generally occurred just downstream of locks and dams. The dredging in this area decreased faster compared to other location within the pools.

- Dredging locations have generally not moved downstream within the UMR pools. However, the intensity of dredging has typically decreased in the upper portion of each pool.

- Generally, there is no concentration of dredging activity at confluences with major tributaries. However, there are several cases where the alluvial fan of a major tributary has induced intense dredging upstream of the mouth of the tributary.

- In many cases, dredging occurs in the same location within each pool, decade after decade.

- Dredging locations are typically associated with flow split locations. Bifurcations of flow generally reduce the sediment transport capacity in the main channel, inducing deposition and the requirement for dredging.

8.1.1.4 Future Geomorphic Conditions

Predicted geomorphic conditions for the Year 2050 include the following:

- Maps of concentrated areas of predicted future geomorphic change were developed for each UMR pool (See Appendix F). As denoted on the maps, the areas of change were grouped into nine general categories of geomorphic processes. For several pools no concentrated areas of geomorphic change were defined. However, it is noted that the overall predicted change for any individual aquatic class may still be significant.

- The total water area within Pools 4 through 26 is predicted to decrease by 1.4 percent by the year 2050, with the major part of that decrease occurring in the upper portion of each pool. However, predictions for individual pools, or even portions of a pool vary considerably, depending on the location along the river and the aquatic class considered. Predicted changes developed for every pool are given in Section 7.2.2.

- For Pools 4 through 26, contiguous and isolated backwater areas are expected to decrease by 2.1 and 3.6 percent, respectively. The major decrease in backwater areas is expected to occur in the upper portion of each pool. The areas of secondary channels and the main channel are predicted to decrease be 2.6 and 0.7 percent, respectively. The area of islands is expected to decrease overall by 2.0 percent. The majority of the erosion of islands is predicted to occur in Geomorphic Reach 3. For many other reaches, the area of islands actually increases. Overall, the perimeter of islands along the pooled reach of the UMR is predicted to decrease by 3.7 percent. It is again emphasized that predictions for any individual pool, or portion of a pool, can vary considerably from these summary results.

- In general, the conditions of the Open River reaches in the Year 2050 are expected to be similar to existing conditions, with the exception that a significant additional percentage of secondary channels and related backwater areas will be filled with sediment. The area of the remaining secondary channels is expected to decrease by at least 40 percent by the year 2050. Smaller secondary channels will be affected first and larger secondary channels last. It is noted; however, that these results are highly dependent on river management decisions.

8.1.2 Illinois Waterway

Specific conclusions of the study related to the IWW include the following:

- The pre-glacial course of the Mississippi River was the middle and lower Illinois River. A diversion caused by glacial ice rerouted the Mississippi River away from the IWW and into its present course.

- Two reaches of similar geomorphic characteristics were identified along the IWW. The reaches are defined as:

  Reach 1 – Starved Rock, Marseilles, Dresden, Brandon Road, and Lockport Pools
  Reach 2 – Alton, La Grange, and Peoria Pools

- Downstream of Starved Rock Lock and Dam, the IWW exhibits relatively consistent geomorphic conditions. It is characteristically low gradient and aggradational. The majority of backwater areas are located along the IWW downstream of the Starved Rock Lock and Dam. Upstream of Starved Rock Lock and Dam, the IWW is much steeper and has limited backwater areas.

- Available sediment size gradation data for the IWW indicate a greater variability in sediment sizes compared to the UMR. Sediments along the IWW navigation channel were found to range from silt- to gravel-sized material.

- Detailed sediment supply estimates for tributaries to the IWW were developed as part of a sediment budget previously prepared for the IWW (Demissie et al., 1992). The sediment budget estimated that 13.8 million tons of sediment are delivered to the IWW valley from tributaries each year. About 5.6 million tons of sediment per year are determined to be discharged along the IWW each year. About 8.2 million tons of sediment are estimated to be deposited within the IWW valley each year.

- Historic dredging data for the IWW is limited. The available data indicate that the majority of dredging is concentrated in Geomorphic Reach 2 (Alton, La Grange, and Peoria Pools) along narrow sections of the waterway. Disposal sites for dredged material along the IWW are limited to narrow portions of bank. Dredged materials placed in such locations likely reenter the IWW and are reworked by dredging as they move along the waterway.

- Plan form overlays developed for the IWW indicate that very little overall change has occurred along the main channel from the confluence with the UMR upstream to the Brandon Road Lock and Dam over the last 50 years. The main channel is surprisingly straight. Backwater areas identified along the channel are more distinct from the main channel compared to backwater areas along the UMR. Relatively small reductions in backwater area were observed from the plan form overlay. However, this observation may be misleading, as the majority of change in backwater area is likely occurring as underwater sediment deposition that would be undistinguishable by the overlay comparison.

- The geologic history of the IWW has predefined the potential future geomorphic conditions along the IWW. The gradient of the stream is much flatter than the UMR and the watershed soils are highly erodible predisposing Reach 2 to aggradation. Human activities only influence the rate and location of sedimentation that occurs along the IWW. Numerous previous studies have been conducted to investigate the conditions of sedimentation along the IWW and its backwater areas. Those studies generally concluded that significant portions of existing backwater areas would be converted to marsh or wetland by the year 2050.

8.2 RECOMMENDATIONS

Overall, recommendations of the study include the following:

8.2.1 Data

The following recommendations pertain to data availability and data collection requirements resulting from the study:

- In view of the extensive database of information and results developed by the current study, existing long-term data collection and monitoring programs for the whole system should be reviewed in order to optimize future data collection efforts.

- Complete aerial coverage for the entire UMR channel system, at average low flow conditions and preferably in early fall when the foliage has been depleted. Aerial coverages should be developed at approximate 10-year intervals. Delineations of aquatic classes should be developed from the aerial photography in order to monitor changes in the system.

- A cross sectional survey of the entire UMR main channel should be conducted, with transects taken at least every river mile (preferable every half-mile) at approximate 10-year intervals. The end points should be tied down with iron stakes and located by GPS coordinates. The transects should extend across the valley, but not only across the main channel. This is important in order to obtain estimate for sediment accumulation in backwaters along the entire length of the pools. The additional data would allow monitoring of sedimentation conditions along the UMR, expansion of the sediment budget to every UMR navigation pool, and facilitate habitat restoration project designs. Consideration should also be given to developing transect information at denser intervals in selected pools to allow the evaluation of the accuracy of half-mile transect spacing in characterizing channel geometry changes.

- The bathymetry of selected backwater areas should be mapped in a comprehensive manner and repeated at appropriate intervals to monitor sediment accumulation rates in backwater areas.

- The size characteristics of sediments in backwater areas downstream of Pool 14 should be determined. Existing information does not comprehensively define those characteristics. The evaluation of historic plan form data indicates that the backwater areas in pools downstream of Pool 14 are significantly smaller than those found in pools upstream and may consequently have a higher relative value as habitat. As it is predicted that about 20 percent of the remaining backwater areas downstream of Pool 14 will be lost by the year 2050, the size characteristics of the involved sediments are needed to define feasible conservation measures.

- Existing suspended sediment measurement stations along the Mississippi River mainstem should be maintained. The long-term records at these locations are invaluable. Investigations should be conducted to confirm or improve bed load transport estimates for the available suspended sediment measurement station locations.

- Existing suspended sediment measurement stations along major tributaries to the UMR should be maintained. The network of available measurement stations should be critically evaluated for its ability to provide adequate long-term monitoring of tributary sediment supply in the basin. It is noted that available suspended sediment measurement records are extremely limited for many tributaries. Furthermore, field data should be collected to confirm or improve bed load estimates for tributaries.

8.2.2 Geomorphology

Recommendations of the study pertaining to the geomorphology of the UMR include:

- Additional research about the potential impacts of global warming on the hydrology and sediment transport of the UMR watershed should be conducted. Although the occurrence of global warming has been documented, the specific impacts of its occurrence are uncertain. Potential impacts may include changes in hydrology and sediment supplies to the UMR.

- The complexity and area of backwaters is considerably greater for the pools upstream of Pool 14 compared to downstream pools. For some pools the backwater areas are increasing. However, it is likely that the bottom bathymetry is simplifying for these pools, especially in the lower windswept portions of the pools.

- The loss of contiguous and isolated backwaters should be monitored downstream of Pool 14. The small amount of backwater areas in locations downstream of Pool 14 increases their relative importance as habitat. Appropriate mitigation measures should be pursued to ensure their long-term preservation.

- The decrease of the limited backwater areas in the Open River segment of the UMR could be slowed or reversed by opening previously closed secondary channels along its length. Historically, flow splits have been associated with main channel dredging. Hence, thorough consideration of such impacts in reopening of secondary channels is necessary.

8.2.3 Sediment Transport

Recommendations of the study pertaining to sediment transport along the UMR include:

- As long-term suspended sediment measurement records become available for tributary measurement stations, estimates of tributary sediment loads used in the sediment budget should be improved. It is noted that in various instances average annual tributary sediment load estimates were developed based on limited suspended sediment transport measurement records. Improved bed load estimates for tributaries should also be developed based on field data.

- Additional efforts should be made to correlate ungaged tributary areas with available tributary suspended sediment measurement stations. Results of the study could be used to develop sediment load estimates for ungaged tributary drainage areas along the UMR.

- Estimates of sediment contributions to the UMR supplied by bank erosion should be developed on a pool by pool basis.

- Additional study of the influence of reservoirs on the sediment supply to the UMR should be conducted. Information on the specific location, age, original storage volume, and sedimentation characteristics of the reservoirs could be used to verify the results of the current study and predictions for future conditions. Of particular interest would be the estimation of the rate of loss of reservoir storage capacity. The results of the sediment budget for the current study indicate that tributary sediment supplies have been reduced by nearly 50 percent over the historic period of record. This implies that an amount of sediment about equal to the total sediment load of the UMR is being trapped somewhere in the watershed. Although improved land use practices are a part of the possible explanation, it is most likely that sediment deposition in reservoirs constitutes the majority of the sediment supply reduction. If so, the rate of reservoir sedimentation may be extremely important to future geomorphic conditions along the UMR.

8.2.4 Dredging

Recommendations of the study pertaining to dredging activities along the UMR include:

- The management of sediment in Pools 4 through 10 has reduced overall dredging requirements. Specifically, the operation of a sediment trap and other dredging in Pool 4, has been determined to have controlled about 80 percent of the bed load sediment supply from the Chippewa River, a major sediment source to the UMR. It is also noted that the dredged materials are now disposed of outside of the active UMR floodplain. One suspected impact from these sediment management actions has been the erosion of islands within Pools 5 through 9. Consideration should be given to optimizing the management scheme for Chippewa River bed load in order to maintain or restore required habitat within the affected pools. It appears from the historic information that the balance between the sediment supply needed to build or maintain islands and the forces eroding islands them can be altered as required, on a pool specific basis, to achieve desired results.

- Results of the historic cross section analysis indicate that dredging requirements in Lower Pool 11 will increase over the next 50 years as the main channel was observed to be filling. The comparison of historic dredging records to tributary bed load supplies implies that the Wisconsin and Turkey Rivers are the primary sources of bed load sediment to lower Pool 11. A bathymetric survey of lower Pool 11 should be conducted to confirm the conclusions about sedimentation in that region. Mitigation measures for this expected condition might include the installation of a sediment trap at the mouth of either the Wisconsin or Turkey Rivers.

- Consideration should be given to expanding the policy used in Pools 4 through 10 of removing dredged materials from the active floodplain, to other portions of the UMR and the IWW. This action would be expected to reduce dredging requirements and accumulation of sediments in backwater areas. This action would be especially helpful in reaches where dredging is currently large such as the area upstream of the confluence with the IWW. Thorough consideration of dredge material removal should be conducted prior to implementation.

- The aggradational nature of the lower IWW (Geomorphic Reach 2) indicates that management actions will be required to maintain or create adequate backwater habitat areas. Dredging should be considered as an integral component of those management actions. Dredging could be utilized to maintain or deepening existing backwater areas, create artificial secondary channels, and form islands along the channel border. Other sediment management alternatives should be explored, including trapping sediment along upstream tributaries.

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APPENDICES

Appendices A-I are on the CD-ROM attached to the Report

Appendices J-K are on nine CD-ROMs and can be requested from the USACE Rock Islands District office

Appendix A

The Report in Adobe Acrobat Format
(CD ROM)

Appendix B

Hydraulic Modeling Results
(CD ROM)

Appendix C

Maps of Historic Dredging
(CD ROM)

Appendix D

Sediment Data
(CD ROM)

D.1. Bed Material Sample Location Maps

D.2. Suspended Sediment Plots

Appendix E

Plan Form Data
(CD ROM)

E.1. Plan Form Statistics for each Pool

E.2. GIS Maps for Historic Plan Form Changes
(CD ROM)

Appendix F

Plan Form Predictions
(CD ROM)

F.1. Plots of Predicted Aquatic area Statistics

F.2. GIS Maps for Predicted Plan Form Changes
(CD-ROM)

F.3. Open River WES 1989 Hydraulic Classification

Appendix G

Plan Form Overlays
(CD ROM)

G.1. Upper Mississippi River

G.2. Open River

G.3. Illinois Waterway

Appendix H

Historic Cross Section Plots
(CD ROM)

Appendix I

Stages for the Plan Form Data
(CD ROM)

Appendix J

Digitized Upper Mississippi River Plan Form Data
(7 CD ROMs: Available from USACE Rock Island District)

J.1. 1930 UMR Brown's Survey Map

J.2. 1930 UMR Brown's Survey Aerial Photography

J.3. 1940 UMR Aerial Photography

J.4. 1989 UMR EMTC Land Cover / Land Use GIS Coverage

Appendix K

Digitized Illinois Waterway Plan Form Data
(2 CD ROMs: Available from USACE Rock Island District)

K.1. 1930-1936 IWW Survey Map and Aerial Photography

K.2. 1994 IWW Photography

REPORT DOCUMENTATION PAGE

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13. ABSTRACT (*Maximum 200 words*)

The methods and results of a detailed evaluation of the cumulative physical effects of the 9-foot Channel Project are presented. The evaluation includes a review of pertinent prior studies, identification of controlling geomorphic characteristics, description of significant human influences and characterization of historic changes along the UMR system. A wide range of existing literature and data are analyzed including historic discharge and sediment measurement records, existing 2-dimensional hydraulic models and information on river regulating structures and dredging activities. Historic changes are determined by identification, delineation, measurement and analysis of approximately 25,000 plan form features and 2,000 channel cross sections. Results of the analyses are used to predict future physical conditions along the UMR. An assessment of cumulative ecological effects is presented in Volume 2 of this report.

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