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Surficial Sediment Characteristics in Pools 4 and 8, Upper Mississippi River

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Surficial Sediment Characteristics in Pools 4 and 8, Upper Mississippi River

by

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Preface

The Long Term Resource Monitoring Program (LTRMP) was authorized under the Water Resources Development Act of 1986 (Public Law 99-662) as an element of the U.S. Army Corps of Engineers' Environmental Management Program. The LTRMP is being implemented by the Environmental Management Technical Center, a U.S. Geological Survey science center, in cooperation with the five Upper Mississippi River System (UMRS) States of Illinois, Iowa, Minnesota, Missouri, and Wisconsin. The U.S. Army Corps of Engineers provides guidance and has overall Program responsibility. The mode of operation and respective roles of the agencies are outlined in a 1988 Memorandum of Agreement.

The UMRS encompasses the commercially navigable reaches of the Upper Mississippi River, as well as the Illinois River and navigable portions of the Kaskaskia, Black, St. Croix, and Minnesota Rivers. Congress has declared the UMRS to be both a nationally significant ecosystem and a nationally significant commercial navigation system. The mission of the LTRMP is to provide decision makers with information for maintaining the UMRS as a sustainable large river ecosystem given its multiple-use character. The long-term goals of the Program are to understand the system, determine resource trends and effects, develop management alternatives, manage information, and develop useful products.

This report was prepared under Task 1.2.1.3, *Establish Experimental Design*, Work Unit B, *Sediment Characterization in LTRMP Study Pools: Empirical Model Testing*, and Task 2.2.5.3., *Obtain Historical and Present-Day Monitoring Data*, Work Unit C, *Acquiring Sediment Type and Distribution Data*, of the Operating Plan (USFWS 1993). This report was developed with funding provided by the Long Term Resource Monitoring Program. Additional funding was provided by the Navigation Studies being conducted by the U.S. Army Corps of Engineers.

Surficial Sediment Characteristics in Pools 4 and 8, Upper Mississippi River

By James T. Rogala

Abstract

Moisture content, bulk density, and organic content of surficial sediments were estimated with a penetrometer in Navigation Pools 4 and 8 of the Upper Mississippi River during 1994 and 1995. Mean moisture content of sediment was low in both Pool 4 (39%, SD = 15.0%) and Pool 8 (34%, SD = 13.7%), suggesting that soft, fine sediments are uncommon in these pools. Sediment in much of the off-channel habitat was found to have similarly low moisture content. Sediment in small backwaters was particularly low in moisture content, although areas with sediment moisture content greater than 70% were found in small backwaters. Sediment in the large backwaters of Pool 4 was similar to sediment in the small backwaters of Pools 4 and 8, while in Pool 8 the large backwaters areas had sediment with a higher mean moisture content of 57% (SD = 14.8%). Only deep, dredged areas in Pool 8 were dominated by sediment with a high moisture content; here the mean moisture content was 67% (SD = 21.1%). The large, open water off-channel area in lower Pool 8 formed by impoundment had sediments similar to those of channel habitats. As a whole, sediment in off-channel habitats in Pools 4 and 8 had low moisture content, which suggests either small inputs of fine sediment or efficient transport of fine sediment through the off-channel habitats.

Introduction

River scientists and managers can use information on sediment characteristics for a variety of studies related to sedimentation, as well as for other investigations. Data on sediment characteristics have been used to delineate zones of sediment transport in lakes (Hakanson 1986) and may serve similarly as an indicator of the extent of soft sediment accretion in river systems. By monitoring sediment characteristics, we can also detect shifts from firm to flocculent sediments or nutrient-poor to nutrient-rich sediments. These changes in sediment characteristics may be important to a variety of biota. In addition, generating maps of sediment characteristics may be useful in habitat mapping and spatial analysis of sediment types. Therefore, it is desirable to collect data at a spatial density that may be suitable for map generation through spatial interpolation between sampling locations.

To this end it is important to develop methods for rapidly measuring sediment characteristics, providing data that might otherwise be difficult or expensive to obtain. Hakanson and Jansson (1983) developed the penetrometer, a device that measures the penetration of objects into the sediment, to rapidly delineate zones of sediment transport. Gaugush (1994) used a modification of such a device in selected areas of limited spatial extent in the Upper Mississippi River System (UMRS). I collected data with the penetrometer in Pools 4 and 8 of the UMRS in 1994 and 1995 to (1) further assess the utility of the penetrometer over a wide range of sediment conditions, (2) develop techniques that may be used to create spatial sediment databases for maps, and (3) begin to build a database of the physical properties of sediments in the UMRS.

Methods

I used a stratified random sampling design to select sampling sites. Initially, I selected strata using the aquatic areas classification for the UMRS developed by Wilcox (1993). This classification was enhanced to include a greater breakdown of backwaters and side channels to provide a more efficient sampling of areas expected to have greater heterogeneity of sediment characteristics. I used several factors for stratification of sampling areas in Pool 8: distance to channels to create buffer areas, water depth, presence of vegetation in 1989 to delineate channels, and size or width of unique areas.

Table 1 shows a simplified description of the strata and summarizes the targeted allocation of sampling effort among the strata. Figure 1 provides a map of the sampling strata for Pool 8.

I performed a random selection of 1,000 sample sites in Pool 8 with the geographic information system (GIS) software ARC/INFO. Field maps of the sample sites were produced with land–water and bathymetry plotted as a background, which were used to locate most sites during sampling. Technicians used a Global Positioning System (GPS) device with 100-m accuracy to locate sites in large, open-water areas. We sampled 783 of the 1,000 selected sites (Fig. 2) between June 21 and September 21, 1994, on 31 sampling dates in Pool 8. Most of the sites not sampled were in the main channel under deep, high-velocity conditions.

The technicians measured the penetration of cones into the sediment at all sampling sites with an in situ penetrometer (Fig. 3). Hakanson (1986) described the penetrometer and its use. The penetrometer has three cones (L1, L2, and L3) of various weights and sizes that penetrate sediments to varying depths. The L1 cone is the largest and the lightest, the L3 cone is the smallest cone and the heaviest, and the L2 cone is between L1 and L3 in both size and weight. The cones are attached to rods that are held in place on the body of the penetrometer. At shallow water sites, we lowered the penetrometer onto the sediments by using an attached pole. The penetrometer was deployed in deep water by a "free-fall" method of lowering the device by the strings holding the rods in place. When the penetrometer is resting on the sediments, the rods are released, which allow the cones to penetrate the sediments. We then lock the rods in place with the strings, retrieve the device, and read the depth of penetration.

We deployed the penetrometer three times at each site to obtain triplicate penetration measurements for each of the three cones. The triplicate deployment was used to minimize the effects of altered penetration due to objects in the sediments. I further hoped to minimize the effects of inconsistent penetration of cones by investigating various methods of reducing the triplicate values for each cone. The three measurements for each cone were reduced to a single value by using five methods: averaging, by using maximum values, using minimum values, averaging the two least deviating values, and averaging the two greatest values.

Technicians collected surficial sediment (top 10 cm) at a randomly selected subset of 80 sites (approximately 10%) of the total sample sites in Pool 8 with a Wildco Sediment Core Sampler (Wildco Wildlife Supply, Saginaw, Michigan) having a 2-inch-diameter core liner. In the laboratory, the sediment was analyzed for moisture content (percent weight loss upon drying at 105 °C), bulk density (dry mass divided by the volume of sample), and organic content (percent weight loss upon ignition at 550 °C). I used the laboratory analysis data from the sediment cores to develop the relation between the penetration of cones and actual sediment characteristics.

To predict sediment moisture content, bulk density, and organic content, I investigated the use of all three cone types as independent variables with step-wise multiple regression analysis. I performed the regression analysis for all five triplicate reducing methods described previously, and selected the best-fitting regression equation (highest R^2) for each sediment characteristic. Transformations were used when needed to linearize relations between cone penetration and sediment characteristics. I predicted moisture content, bulk density, and organic content with the regression equations for those sites where sediment cores for laboratory analysis were not obtained.

In 1995, I used similar sampling methods and data analysis for Pool 4. Lake Pepin, a large, natural lake in Pool 4, was not sampled. On the basis of my results from Pool 8, technicians sampled no sites in the main channel and a reduced number of sites in the main channel border. This, along with the smaller amount of backwater area in Pool 4, resulted in the selection of 500 potential sample sites providing a sampling density about equal to that of Pool 8. Fewer strata were used to distribute sampling in Pool 4 because buffer strata were not used and no impounded area or deep backwater areas exist in Pool 4. I sampled 478 of the 500 randomly selected sites between May 18 and August 9, 1995, on 20 sampling dates. I located all sites with a GPS receiver with 15-m accuracy. Table 1 summarizes the targeted and actual sampling for Pool 4; maps show sampling strata (Fig. 4) and sampling locations (Fig. 5). A subset of 92 sites (about 20%) were randomly selected for sediment core collection and analysis. I chose the increase in the percentage of the subsetted sites to ensure adequate core data for developing the relations between penetration and sediment characteristics. I calibrated the penetrometer at Pool 4 independently from the Pool 8 calibration.

I created a GIS database for sediment characteristics by merging the estimated sediment characteristics for each sampling point with the GIS point coverage generated from the random selection of sampling points. To create a continuous surface of data, I used GIS data for moisture content of sampling locations to interpolate values spatially between sampling locations. I evaluated several surfacing algorithms and a number of options for search radius (sample) and weighing of data based on distance (power) before selecting an interpolation method. I selected an inverse distance weighted interpolation with a power of one and a sample of nine. My interpolation method also included restricting interpolation to within sampling strata found to be significantly different from other sampling strata. I then combined interpolated surfaces for each stratum, or groups of strata, to create a pool coverage. Restricting interpolation to within strata provided an interpolation barrier so that data from nearby areas of a different stratum, which were shown to have different sediments, did not influence the interpolation. I did not interpolate data in strata where I collected no data or a greatly reduced set of data.

Results

Penetrometer Calibration

Using the laboratory data from the sediment core samples, I calibrated the penetrometer at Pools 4 and 8 to estimate moisture content, bulk density, and organic content using regression equations as described previously. The sample size of sediment cores available to develop the regression equations varied, with 45 samples for bulk density in Pool 8, 80 samples for water content and organic content in Pool 8, and 92 samples for all parameters in Pool 4. In all instances, at least two of the three cones contributed significantly to the model in the presence of the other variables. Table 2 gives the regression equations for Pools 4 and 8 for moisture content, bulk density, and organic content.

The strongest correlations between cone penetration (x, the independent variable) and sediment characteristics (y, the dependent variable) were found in sediment moisture data. The highest R^2 (0.79) for Pool 8 sediment moisture was obtained with y^2 transformed data using the maximum two values of the triplicate for each cone. The best fit in Pool 4 was lower (R^2 = 0.67) and obtained with y^2 transformed data using the maximum value of the triplicate for each cone. I identified a group of sites in Pool 4, within a single backwater bay adjoining the north end of Lake Pepin near Bay City, Wisconsin, as fitting the regression line poorly. Using a homogeneity of slopes linear regression model, I found the relation between moisture content and penetration to have different slopes (P = 0.05) for the sites within this bay and other sites in Pool 4. When I removed all five coring sites within that backwater bay, I obtained a higher R^2 (0.75) with transformed data using the maximum value of the triplicate for each cone.

I also found sediment density to be highly correlated to cone penetration. In Pool 8, I obtained the highest R^2 (0.70) with a square root of y transformation using the two least-deviating penetration values for each cone. A square root of y transformation was also used in Pool 4, but the maximum penetration value for each cone provided the best fit (R^2 = 0.65). As with the data for moisture content, omitting the Lake Pepin bay data increased the correlation (R^2 = 0.73).

Using cone penetration, I found organic content to be the least predictable of the three characteristics. The strongest correlation between cone penetration and organic content in Pool 8 was obtained by using the average of the two greatest values of the triplicate for each cone ($R^2 = 0.59$). I obtained the best fit for all data in Pool 4 by using the maximum penetration value for each cone ($R^2 = 0.55$), which increased to $R^2 = 0.61$ with the Lake Pepin bay sites removed.

Sediment Characteristics in Pool 8

Patterns in water content, bulk density, and organic content are often similar in aquatic sediment because these physical properties are related. However, the similarity of these physical properties of sediment in my results may be enhanced because all three properties were predicted from penetrometer measurements. Sediment in deep backwaters of Pool 8 had the highest mean moisture content (66.1%), highest mean organic content (12.6%), and lowest mean bulk density (0.48 g/mL). Sediment in large backwaters were second highest in mean moisture content (57.2%) and mean organic content (8.32%) and had the second lowest mean bulk density (0.69 g/mL). The small, shallow backwaters were next with a mean moisture content of 43.0%, mean organic content of 5.96%, and mean bulk density of 0.95 g/mL. Sediment in the other five strata were similar in mean moisture content (ranging from 25.2% to 31.4%), mean organic content (ranging from 2.51% to 3.12%), and mean bulk density (ranging from 1.25 to 1.33 g/mL). Figure 6 shows means and standard deviations of water content, bulk density, and organic content for sediment in each sampling stratum.

I used a Tukey's multicomparison procedure to determine differences in sediment characteristics among strata. The water content, bulk density, and organic content of sediment in each of the three backwater strata (deep backwater lakes, large backwater lakes, and small shallow backwaters) differed significantly ($P = 0.05$) from the other five strata (Table 3). All three sediment characteristics were significantly different between small, shallow backwaters and the other two backwater types. I also detected significant differences in organic content between sediment in large backwater lakes and sediment in deep backwater lakes, but found no significant differences between these two backwater types for sediment moisture content and sediment bulk density. No significant differences were found among other strata.

Sediment characteristics in Pool 8 were determined by weighing sediment characteristics at each sample site on the basis of the area of each stratum and the number of samples in each stratum. Because no sites in the main channel strata were sampled and only a third of the main channel border sites were sampled, these areas were not included in the summary for Pool 8. For sediment in Pool 8, the mean moisture content was 34.0%, mean bulk density was 1.17 g/mL, and mean organic content was 3.89% (Fig. 6). The frequency distributions for moisture content, bulk density, and organic content for sediment in Pool 8, by strata, are illustrated in Figure 7. A map of Pool 8 sediment moisture content was generated through interpolation between data locations (Fig. 8).

Sediment Characteristics in Pool 4

Patterns in water content, bulk density, and organic content of sediment in Pool 4 differed somewhat from the same strata types in Pool 8. Sediment in the small shallow backwaters had the highest mean moisture content (45.2%), highest mean organic content (5.80%), and lowest mean bulk density (0.83 g/mL). Large backwaters contained the stratum with the second highest mean moisture content (41.9%) and mean organic content (5.07%) and had the second lowest mean bulk density (0.89 g/mL). Sediment in the three channel strata (main channel border, large side channels, and small side channels) were similar in mean moisture content (ranging from 24.2% to 28.5%), mean organic content (ranging from 1.69% to 2.54%), and mean bulk density (ranging from 1.16 to 1.25 g/mL). Figure 9 shows means and standard deviations of water content, bulk density, and organic content for sediment in each sampling stratum.

Using a Tukey's multicomparison procedure, I detected significant differences ($P = 0.05$) for moisture content, bulk density, and organic content between sediment in the two backwater strata (large backwater lakes and shallow backwaters) and sediment in the channel strata (Table 3). I found significant differences between sediment in the two backwater strata, but no significant differences among sediment in channel strata (main channel border, large side channels, and small side channels).

I determined sediment characteristics for Pool 4 using the same methods as for Pool 8. The summary data for Pool 4 does not include Lake Pepin, the Lake Pepin bay described previously, the main navigation channel, or the main channel border. For sediment in Pool 4, the mean moisture content was 39.9%, mean bulk density was 0.93 g/mL, and mean organic content was 4.75 (Fig. 9). The frequency distributions for moisture content, bulk density, and organic content for sediment in Pool 4, by strata, are illustrated in Figure 10. A map of Pool 4 sediment moisture content was generated through interpolation between data locations (Fig. 11).

Discussion

Predictive Success With the Penetrometer

Better relations than obtained here between the penetrometer and sediment characteristics may be obtained in less dynamic systems. In the UMRS, areas of sediment accumulation, transport, or erosion may shift through time as a result of the highly variable river flow. Therefore, fine and coarse sediments are probably layered. The layering will alter the sediment characteristics estimated with a penetrometer because a coarse sediment layer on the surface will impede penetration to buried, high-moisture content sediments. Similary, the surficial (top 10-cm) sediments may or may not differ from subsurface (> 10-cm) sediments; thus, penetration to a great depth may not indicate softer sediments at the surface than found in penetration to a lesser depth. For example, penetration at two sites may be 20 cm and 40 cm, but the difference may reflect subsurface sediment differences and not surficial sediment differences. I found the L3 cone often penetrates beyond the surficial sediments and, in some instances, penetrated to depths greater than 40 cm.

Another consideration derived from the Pool 8 sampling is a limitation in using the penetrometer in deep, high-velocity habitats. As mentioned earlier, I did not sample some of the main channel border sites nor all of the main channels sites because of the difficulty in deploying the penetrometer. Shallow, high-velocity habitats were sampled by using the pole on the penetrometer to assure proper deployment on the bottom, and deep, low-velocity habitats were sampled with a "free-fall" penetrometer. However, in deep, high-velocity areas I could not confirm that the penetrometer had been properly deployed. I noted highly variable readings in the penetration, which probably indicated that the penetrometer was not vertically aligned or perhaps it was placed on a surface with deep dunes.

Sediment Characteristics of Pools 4 and 8

Because all three characteristics have similar patterns, I limit discussions here to moisture content of the sediments. Hakanson and Jansson (1983) established an ability to predict areas of fine sediment accumulation from the moisture content of sediment in lakes. Gunkel et al. (1984) suggested that this relation also exists in reservoirs. Therefore, data presented here on the moisture content of sediments in the Upper Mississippi River may provide estimates of the amount of area where fine sediment is accumulating.

In general, the moisture content of sediments in Pools 4 and 8 was lower than would be expected in a system undergoing fine sediment accretion. In lakes, Hakanson and Jansson (1983) suggested that areas with greater than 70% moisture content are probably depositional areas for fine sediments. Means of 39.2% moisture content for sediment in

Pool 4 and 34.0% moisture content for sediment in Pool 8 for all areas excluding the main channel and the main channel border do not suggest extensive areas of fine sediment accretion in the pools as a whole. Only 2.5% (77 ha) of the study area of Pool 4 and 2.8% (198 ha) of the study area of Pool 8 are estimated to have sediment with a moisture content greater than 70% (Figs. 7 and 10). Even with all channel areas and the impounded area in Pool 8 excluded, the percentage of the backwater area having sediment moisture content greater than 70% is only 3.3% for Pool 4 and 11.0% for Pool 8.

The poolwide mean for the moisture content of sediment in Pool 8 is strongly influenced by the impounded area that makes up 44% of its surface area. The impounded area is often thought of as an aging reservoir with much soft sediment accretion (Fremling and Claflin 1984; Nielsen et al. 1984). However, mean moisture content for sediment in the impounded area was only 30.2% in this survey, which suggests that little fine sediment accretion is presently occurring in this area. Only a small fraction of this area is made up of high-moisture content sediments (Fig. 7). Coarse sediment deposition in deltalike areas near the main channel may contribute to the low mean moisture content of sediment in the impounded area.

Other backwater types also exhibited characteristics unlike areas with soft sediment accumulation. Sediment in the small, shallow backwater strata in both Pools 4 and 8, although significantly differing from channel areas, as found to contain low-moisture content sediment, with means of 45.2% in Pool 4 and 43.0% in Pool 8. The low-moisture content sediment in small backwaters may reflect the dominance of river flows during high water, which may transport previously deposited fine sediments or deposit coarse sediments. Therefore, in a dynamic river system such as the UMRS, fine sediment deposition over long periods may be limited to a small portion of the small, highly connected off-channel area. This is evident in the small fraction of these backwaters with high-moisture content sediments (Figs. 7 and 10).

The mean moisture content was low for sediment in large backwaters as well, although some individual large backwaters had sediment with high-moisture content. Sediment in large backwaters in Pool 4 had particularly low-moisture content (41.9%) compared with that in Pool 8 (57.2%). This lower moisture content may largely be because coarse sediments are deposited in the large lakes below the Chippewa River located in the middle of Pool 4 (Fremling and Claflin 1984). Those lakes are also likely to have little fine sediment delivered from the Mississippi River because of the high trapping efficiency of Lake Pepin (Maurer et al. 1995), located just upstream of the mouth of the Chippewa River. The lower sediment moisture content may also reflect the flow-through nature of most large backwaters in Pool 4 not found in Pool 8.

Only sediment in the deep backwater stratum in Pool 8 had a mean moisture content near the 70% that Hakanson and Jansson (1983) suggested as an indicator of fine sediment accretion in lakes. All these backwaters are actually borrow pits, deep areas created by dredging. Thus, the data suggest that the only areas of uniform fine sediment deposition are in human-made sediment traps, but these areas compose only a small fraction of the total backwater area in Pool 8 (Fig. 7). Other backwaters, whether existing before impoundment or created by impoundment, seem to have low trapping efficiency.

Two issues related to the previous discussions should be clarified: First, because coarse sediments are periodically scoured and deposited, the variability in accretion over time can influence the detection of accreted fines. For example, I sampled in Pool 8 just 1 yr after a high-discharge year and in Pool 4 just 2 yr after a high-discharge year. The high river flows associated with the high-discharge period may have removed recently deposited fines that had not compacted; the flow may also have buried previously deposited fine sediments with coarse sediment during high discharge. Such patterns in sedimentation were suggested in the sediment cores obtained. As previously described, buried fine sediment would not be detected by the methods used in this survey. Second, compaction of accumulated fines can result in low-moisture sediments. The low fetch in small backwaters of the UMR may enhance sediment compaction, although shallow depths may provide for sediment resuspension despite the low fetch. Compaction is also greatly accelerated if sediments are dewatered and allowed to dry. However, it is unlikely dewatering is a factor in the present survey because water level records indicated that none of the sites sampled had been dewatered in the past 30 yr.

I used the buffer strata in Pool 8 to investigate the sediment type gradient between off-channel strata and channel strata. Data did not suggest that the buffer strata were transitional areas between low-moisture and high-moisture sediments. I would expect variability of sediment character to be higher in a transitional area, but standard deviations were less for buffer areas as a whole. This may be a result of (1) poor classification of boundaries between channel and off-channel types, (2) inadequate size in the buffer distance to catch the transition zone, or (3) slight gradients between channel and nonchannel areas. The moisture content of sediment in the buffer areas was similar to channel types, suggesting that a slight gradient may exist, and high-moisture content sediments are found only at a great distance from the channels.

The maps created through interpolation for sediment moisture content can be created for bulk density and organic content as well. However, all these maps should be used with caution and must only be used with knowledge of the location of sample points and an understanding of interpolation algorithms. Even the rather extensive sampling in this study provides sparse data compared with the data needed to reasonably estimate spatial sediment characteristics. General trends can be observed with the maps, but characteristics interpolated within individual backwater areas may be based on limited or no data. Also, the use of strata to restrict interpolation between strata presents a misconception that sediment characteristics change sharply at those boundaries. As previously discussed, these sharp transitions do not occur for most backwaters.

Conclusions

Areas with high water content, high organic content, and low-bulk density sediments were uncommon in both Pools 4 and 8. The estimated area of high-moisture sediments (> 70% moisture) in both Pools 4 and 8 was less than 3% of the total area of the pool, excluding the main channel. Only human-made dredge holes in Pool 8 had a high mean moisture content (66.1%). With the exception of the impounded stratum in Pool 8, sediment types of backwater strata differed significantly from channel strata.

The summary data provided by this survey can be used to establish a baseline of sediment conditions that can be used to detect large-scale changes or differences among pooled reaches. In the future, I may be able to detect shifts of sediment character as a result of reservoir aging or changes in resource management with replication of this sampling design. The ability to detect differences, whether spatially or temporally, would however be dependent on the sample size and heterogeneity of the sediment character. The significant differences detected among some strata types suggest that the sampling in this survey was sufficient for detecting some differences.

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Table 1. Descriptions of the sampling strata and distribution of sampling among stata for Pools 8 and 4.

Sampling strata	Description
Main navigation channel	Area for navigation as defined by channel buoys and markers
Main channel borders	Area between the main channel shore and the navigation channel
Large side channels	Unbraided channels >100 m wide
Small side channels	Braided channels or unbraided channels <100 m wide
Buffer between channels and backwaters	Area 40 m wide between channels and backwaters
Small shallow backwaters	Backwaters <25 ha or backwaters with >1 outlet and <100 ha
Deep backwaters	Areas in backwaters dredged to a depth of >3 m
Large backwater lakes	Backwater lakes >100 ha or lakes with one outlet and >25 ha
Buffer between impounded and channels	Area 40 m wide between channels and the impounded area
Impounded backwater areas	Area of large fetch upstream of the dam

	Sampling strata	Percentage of total area	Target percentage of total samples	Actual number of sites sampled	Actual percentage of sampled sites	Density of sampling (points per 100 ha)
Pool 8						
	Main navigation channel	7.4	5	0	0.0	0.0
	Main channel borders	7.4	10	30	3.8	4.9
	Large side channels	6.2	8	74	9.5	14.4
	Small side channels	5.4	8	64	8.2	14.3
	Buffer between channels and backwaters	4.9	10	98	12.5	27.0
	Small shallow backwaters	16.2	27	230	29.4	17.2
	Deep backwaters	0.4	1	8	1.0	23.4
	Large backwater lakes	4.7	8	44	5.6	11.3
	Buffer between impounded and channels	3.1	5	39	5.0	15.1
	Impounded backwater areas	44.1	20	196	25.0	5.4
	Total			783		10.3
Pool 4						
	Main channel borders	15.1	5	18	3.7	3.2
	Large side channels	9.4	10	49	10.3	14.0
	Small side channels	9.8	10	48	10.0	13.1
	Small shallow backwaters	24.1	35	170	35.6	19.0
	Large backwater lakes	41.6	40	193	40.4	12.5
	Total			478		12.8

Table 2. Stepwise regression equations for moisture content, bulk density, and organic content in Pools 4 and 8. Cone penetration (L1, L2, and L3) is measured in centimeters and the penetration value is obtained through reduction of triplicate data.

Pool	Sediment characteristic	Regression equation	R^2
4			
	Moisture content (%)	$\sqrt{(-29.68 - 52.74 * L1 + 193.13 * L2 + 65.26 * L3)}$	0.75
	Bulk density (g/mL)	$(1.211 - 0.0238 * L2 - 0.0107 * L3^2)$	0.73
	Organic content (%)	$(0.00875 + 0.4793 * L2 + 0.149 * L3)$	0.61
8			
	Moisture content (%)	$\sqrt{(-693.08 + 176.16 * L2 + 137.6 * L3)}$	0.79
	Bulk density (g/mL)	$(1.267 + 0.0406 * L1 - 0.021 * L2 - 0.0231 * L3^2)$	0.70
	Organic content (%)	$(-0.471 + 0.2565 * L2 + 0.3309 * L3)$	0.59

Table 3. Significant differences ($P = 0.05$) in sediment characteristics among strata as detected by using Tukey's multicomparison procedure. Significant differences are indicated by *** for Pool 8 moisture content and bulk density (*a*), Pool 8 organic content (*b*), and Pool 4 moisture content, bulk density, and organic content (*c*).

(a)

Sampling strata	MCB	SSC	LSC	BCB	SBW	DBW	LBL	BCI	IMP
MCB		0	0	0	***	***	***	0	0
SSC	0		0	0	***	***	***	0	0
LSC	0	0		0	***	***	***	0	0
BCB	0	0	0		***	***	***	0	0
SBW	***	***	***	***		***	***	***	***
DBW	***	***	***	***	***		0	***	***
LBL	***	***	***	***	***	0		***	***
BCI	0	0	0	0	***	***	***		0
IMP	0	0	0	0	***	***	***	0	

(b)

Sampling strata	MCB	SSC	LSC	BCB	SBW	DBW	LBL	BCI	IMP
MCB		0	0	0	***	***	***	0	0
SSC	0		0	0	***	***	***	0	0
LSC	0	0		0	***	***	***	0	0
BCB	0	0	0		***	***	***	0	0
SBW	***	***	***	***		***	***	***	***
DBW	***	***	***	***	***		***	***	***
LBL	***	***	***	***	***	***		***	***
BCI	0	0	0	0	***	***	***		0
IMP	0	0	0	0	***	***	***	0	

(c)

Sampling strata	MCB	SSC	LSC	SBW	LBL
MCB		0	0	***	***
SSC	0		0	***	***
LSC	0	0		***	***
SBW	***	***	***		***
LBL	***	***	***	***	

MCB = Main channel borders
SSC = Small side channels
LSC = Large side channels
BCB = Buffer between channels and backwaters
SBW = Small shallow backwaters
DBW = Deep backwaters
LBL = Large backwater lakes
BCI = Buffer between impounded areas and channels
IMP = Impounded backwater areas

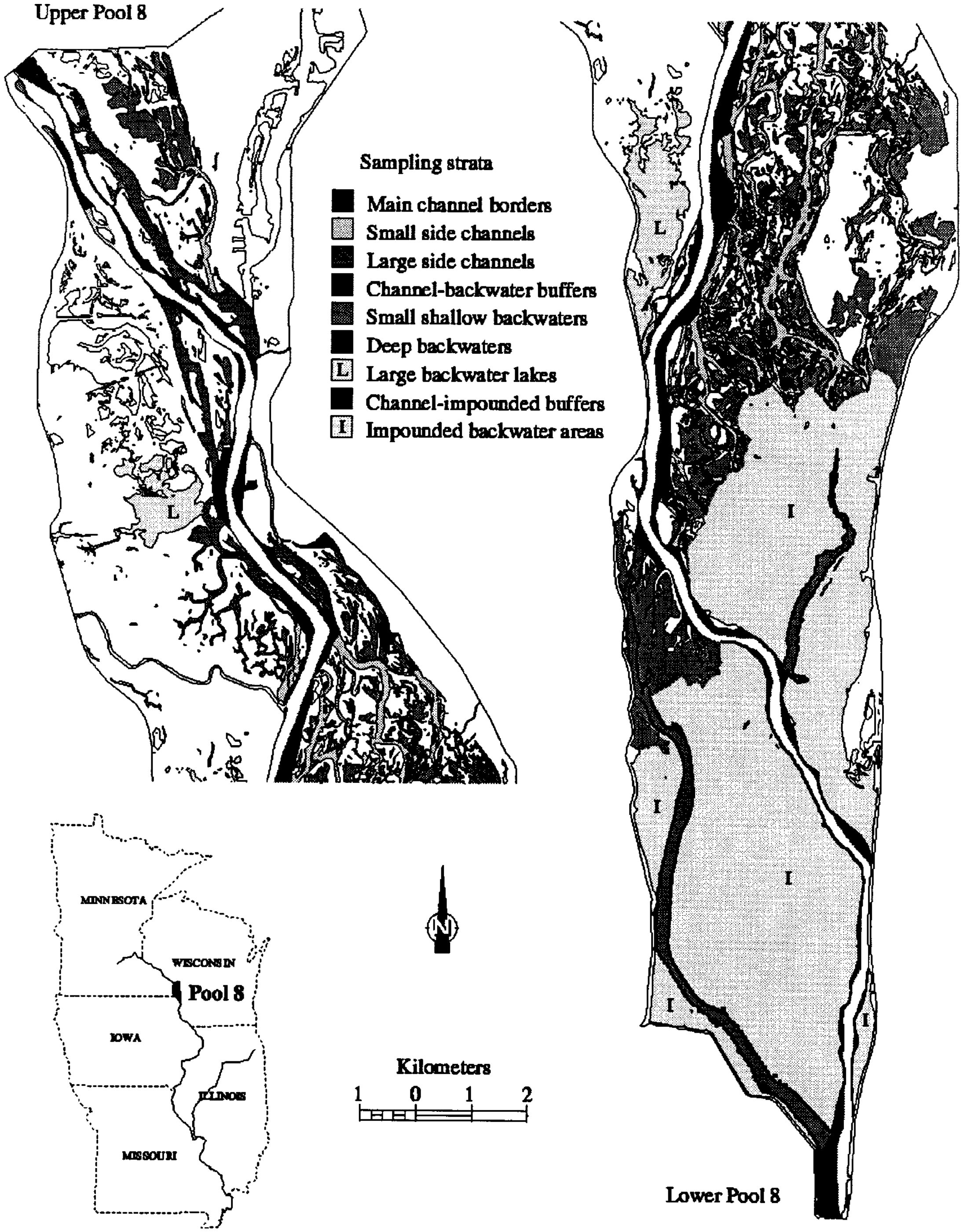


Figure 1. Map of the sampling strata used to allocate sampling across Pool 8.

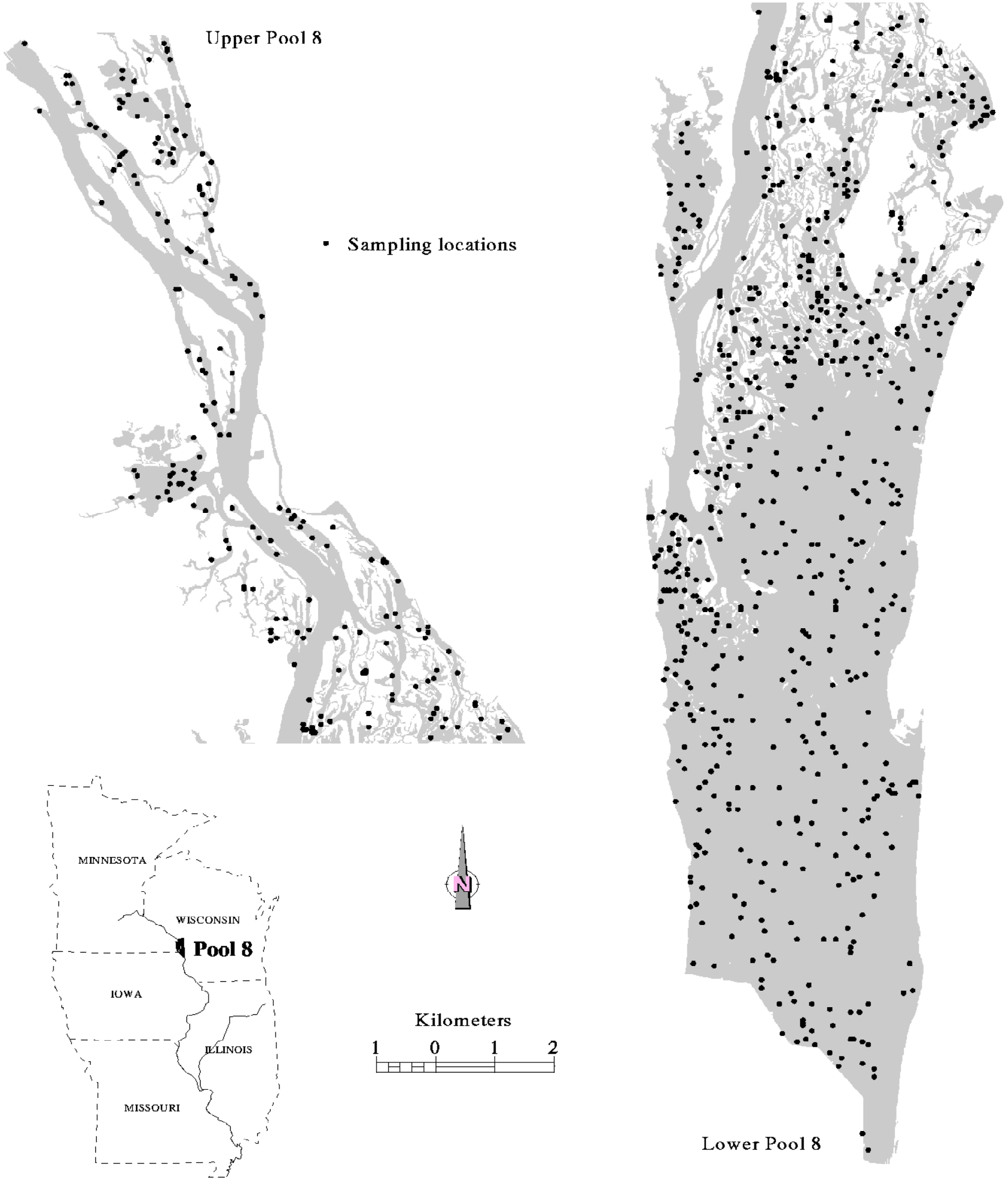
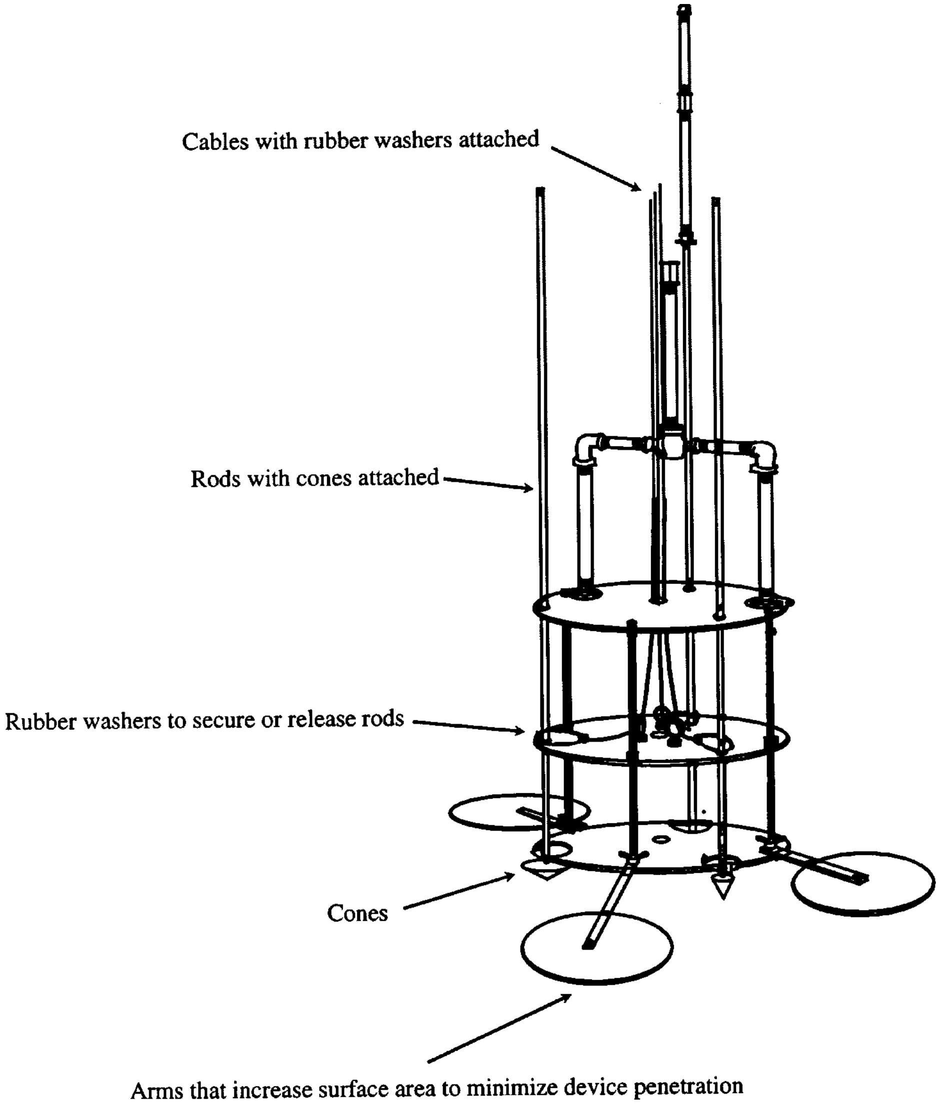


Figure 2. Locations of sampling sites used in the sediment survey of Pool 8 in 1994.



Cone	Cone and rod weight (g)	Cone height (cm)	Cone top angle (°)
L1	250	3	90
L2	300	3	30
L3	500	1.5	30

Figure 3. Illustration of the penetrometer and the size and weight of the cones.

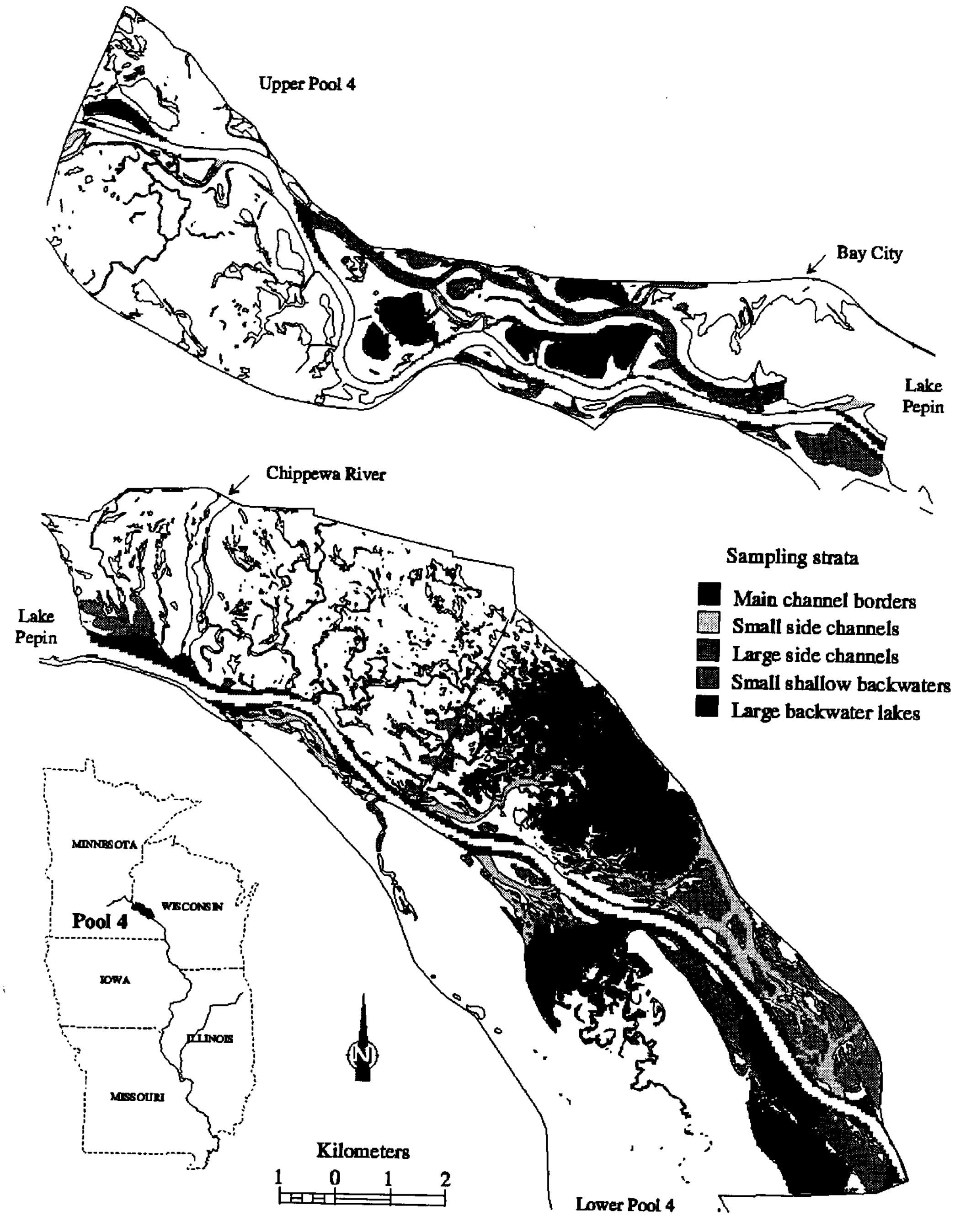


Figure 4. Map of the sampling strata used to allocate sampling across Pool 4.

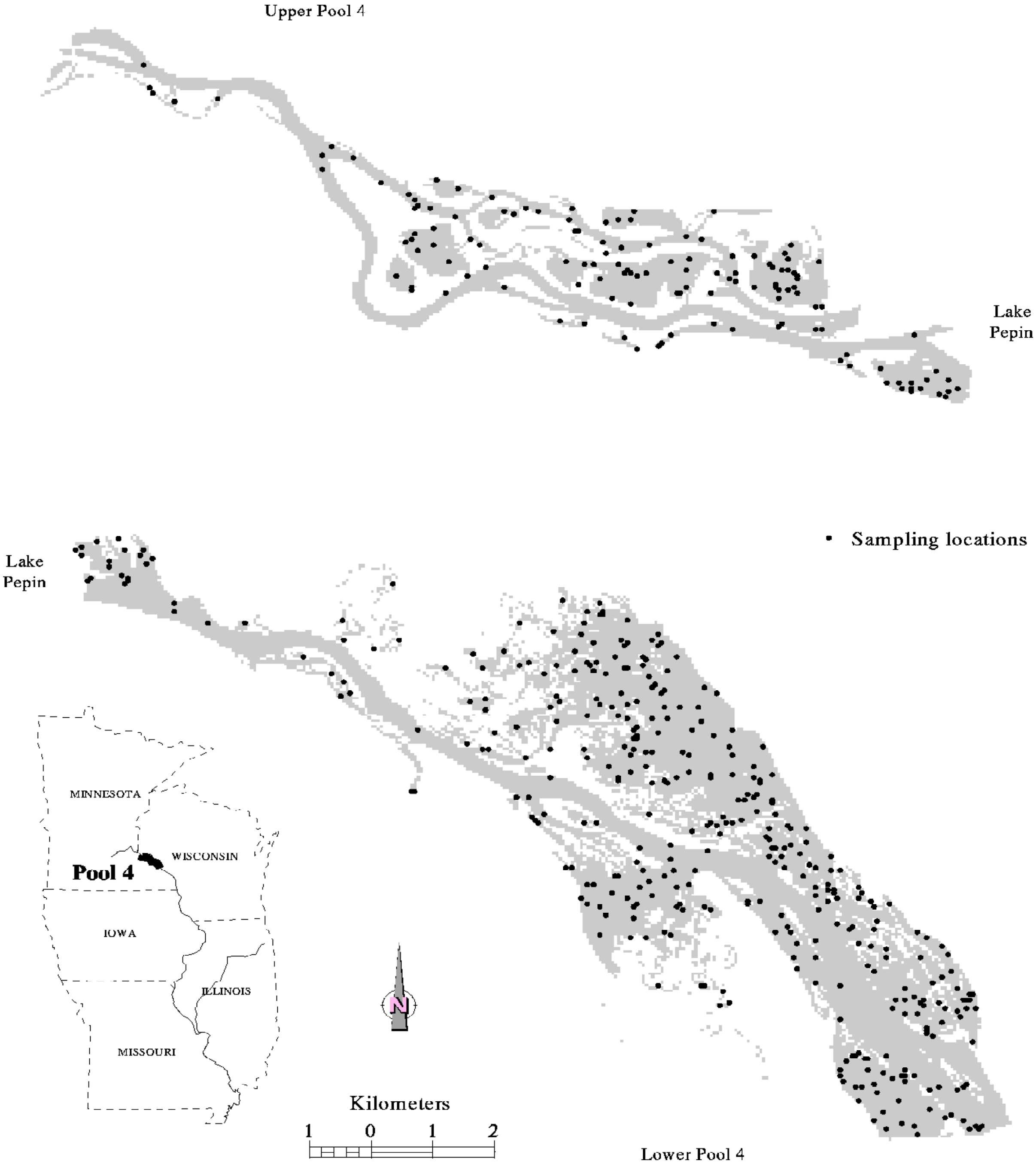
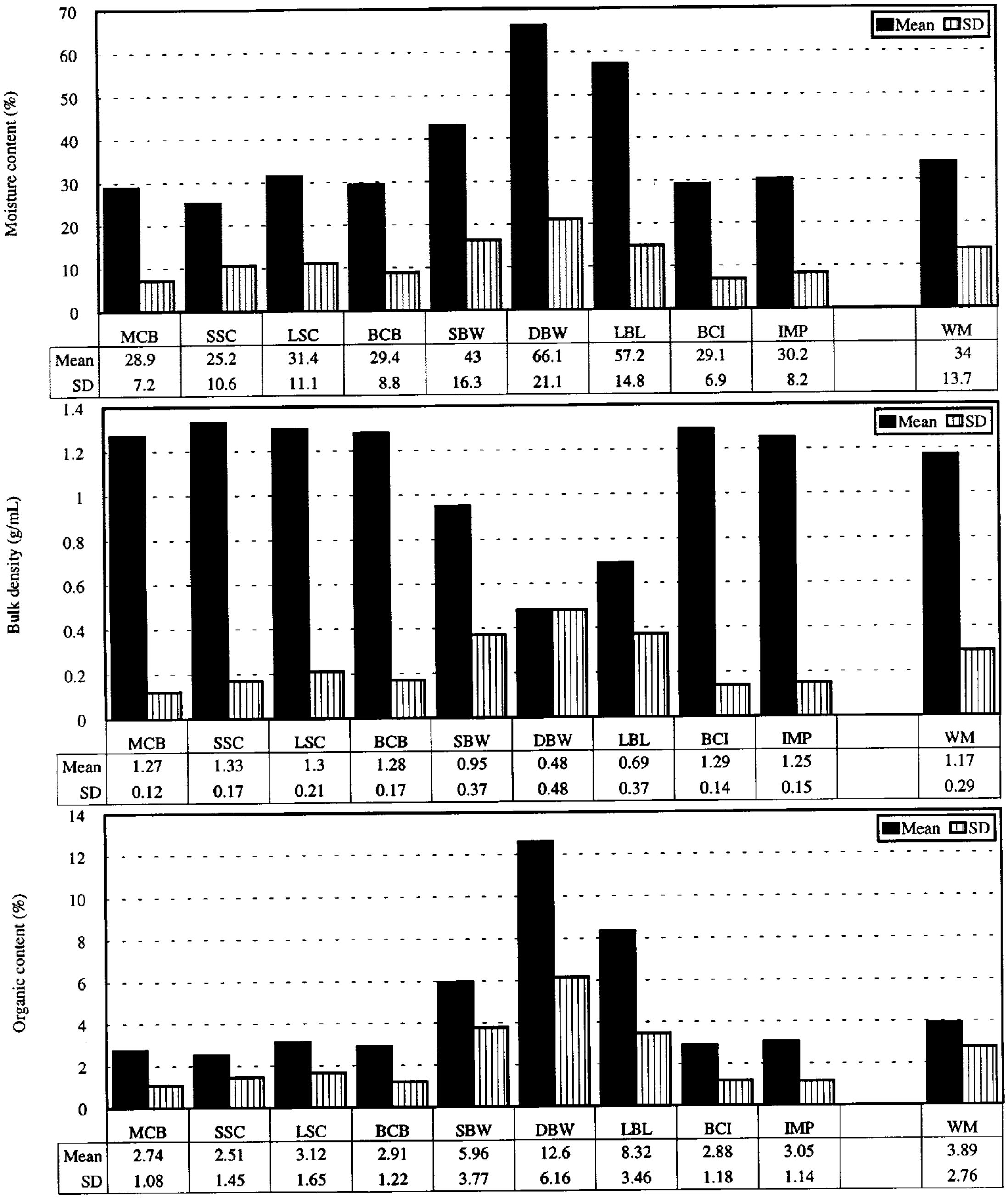


Figure 5. Locations of sampling sites used in the sediment survey of Pool 4 in 1995.



	MCB	SSC	LSC	BCB	SBW	DBW	LBL	BCI	IMP		WM
Mean	28.9	25.2	31.4	29.4	43	66.1	57.2	29.1	30.2		34
SD	7.2	10.6	11.1	8.8	16.3	21.1	14.8	6.9	8.2		13.7

	MCB	SSC	LSC	BCB	SBW	DBW	LBL	BCI	IMP		WM
Mean	1.27	1.33	1.3	1.28	0.95	0.48	0.69	1.29	1.25		1.17
SD	0.12	0.17	0.21	0.17	0.37	0.48	0.37	0.14	0.15		0.29

	MCB	SSC	LSC	BCB	SBW	DBW	LBL	BCI	IMP		WM
Mean	2.74	2.51	3.12	2.91	5.96	12.6	8.32	2.88	3.05		3.89
SD	1.08	1.45	1.65	1.22	3.77	6.16	3.46	1.18	1.14		2.76

MCB = Main channel borders
SSC = Small side channels
LSC = Large side channels
BCB = Buffer between channels and backwaters
SBW = Small shallow backwaters
DBW = Deep backwaters
LBL = Large backwater lakes
BCI = Buffer between impounded areas and channels
IMP = Impounded backwater areas

Figure 6. Means and standard deviations (SD) for moisture, density, and organic content for the nine sampling strata in Pool 8. Included are weighted means (WM) for each sediment characteristic for Pool 8, excluding the main channel and main channel border.

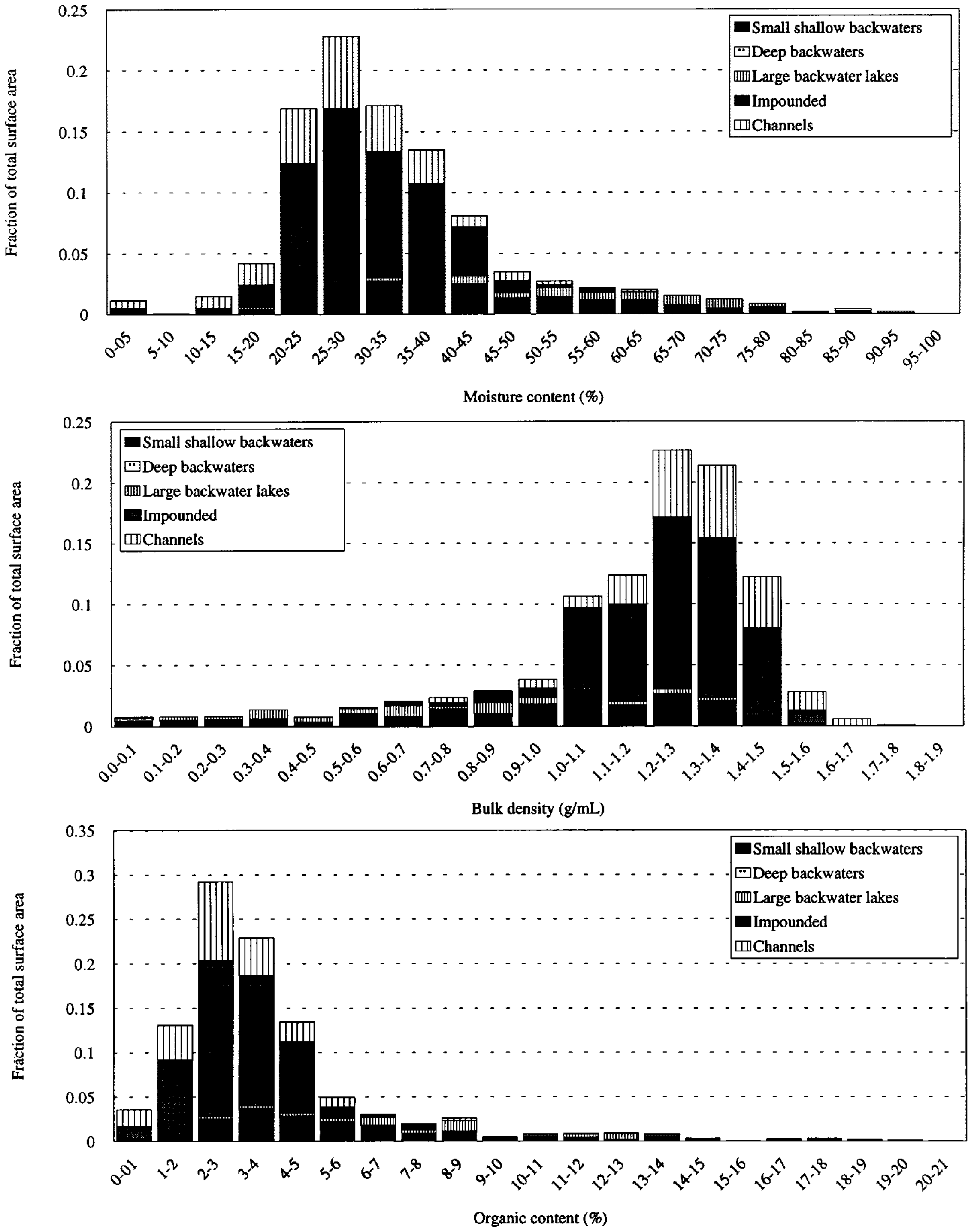


Figure 7. Frequency distribution for moisture content, bulk density, and organic content for Pool 8. The bars for each strata are weighted on the basis of the area of each stratum, and the pool frequency distribution is the total of the stacked bars.

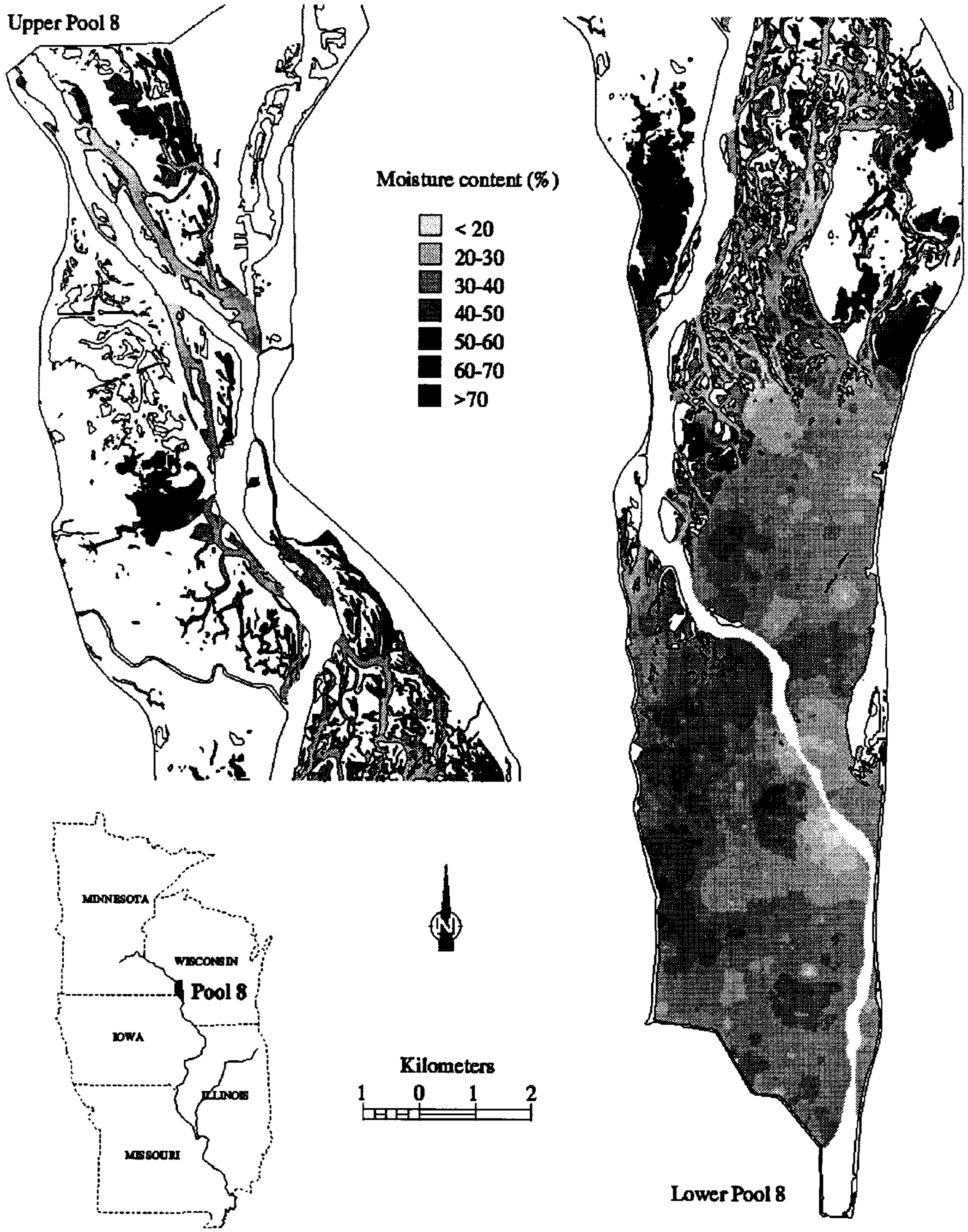
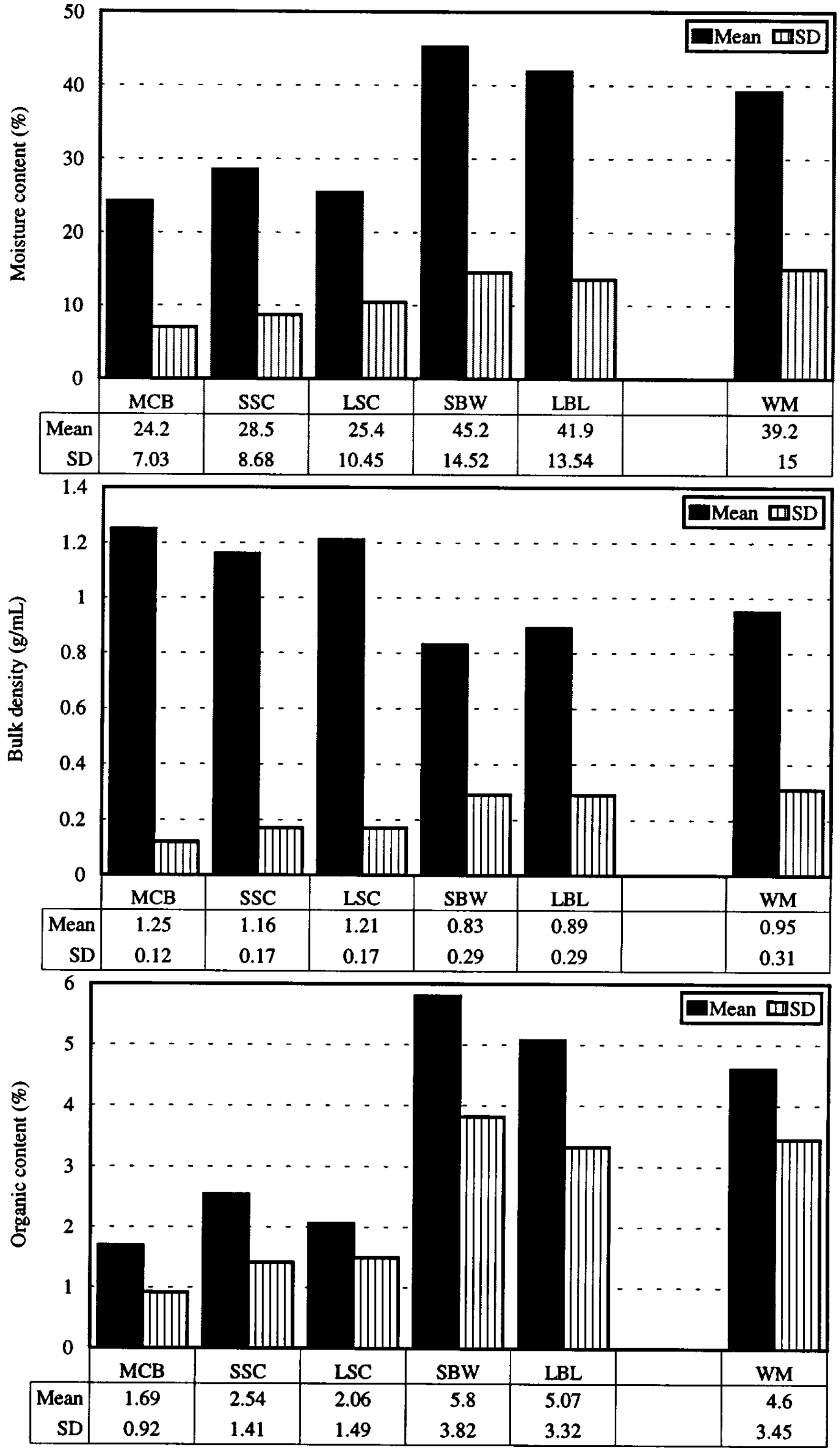


Figure 8. Map of sediment moisture in Pool 8 created by interpolating between sample points. Note that values were not interpolated in the main channel and main channel border because those strata were only partly sampled.



	MCB	SSC	LSC	SBW	LBL		WM
Mean	24.2	28.5	25.4	45.2	41.9		39.2
SD	7.03	8.68	10.45	14.52	13.54		15

	MCB	SSC	LSC	SBW	LBL		WM
Mean	1.25	1.16	1.21	0.83	0.89		0.95
SD	0.12	0.17	0.17	0.29	0.29		0.31

	MCB	SSC	LSC	SBW	LBL		WM
Mean	1.69	2.54	2.06	5.8	5.07		4.6
SD	0.92	1.41	1.49	3.82	3.32		3.45

MCB = Main channel borders
SSC = Small side channels
LSC = Large side channels
SBW = Small shallow backwaters
LBL = Large backwater lakes

Figure 9. Means and standard deviations (SD) for moisture, density, and organic content for the five sampling strata in Pool 4. Included are weighted means (WM) for each sediment characteristic for Pool 4, excluding Lake Pepin, the main channel, and the main channel border.

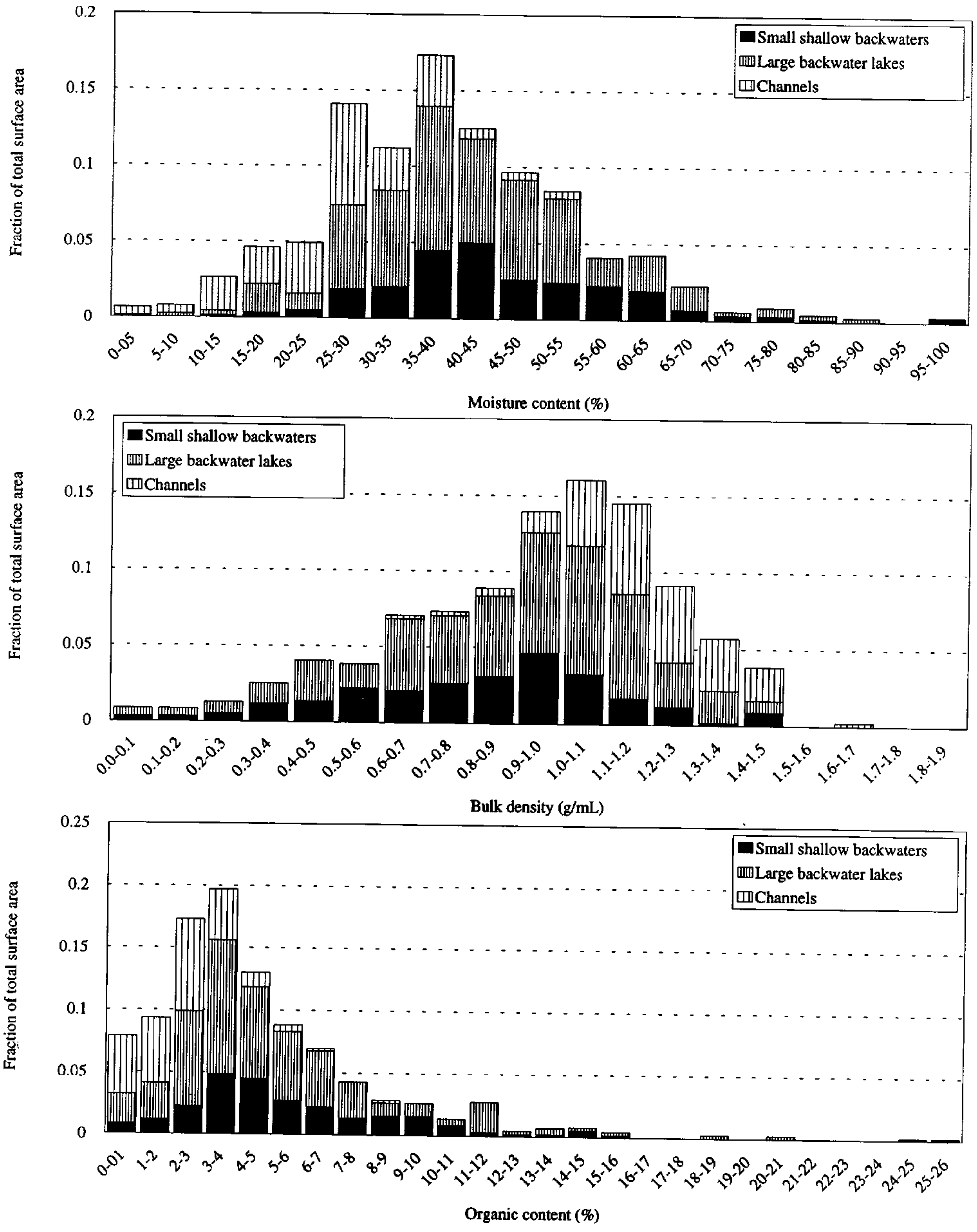


Figure 10. Frequency distribution for moisture content, bulk density, and organic content for Pool 4. The bars for each strata are weighted on the basis of the area of each stratum, and the pool frequency distribution is the total of the stacked bars.

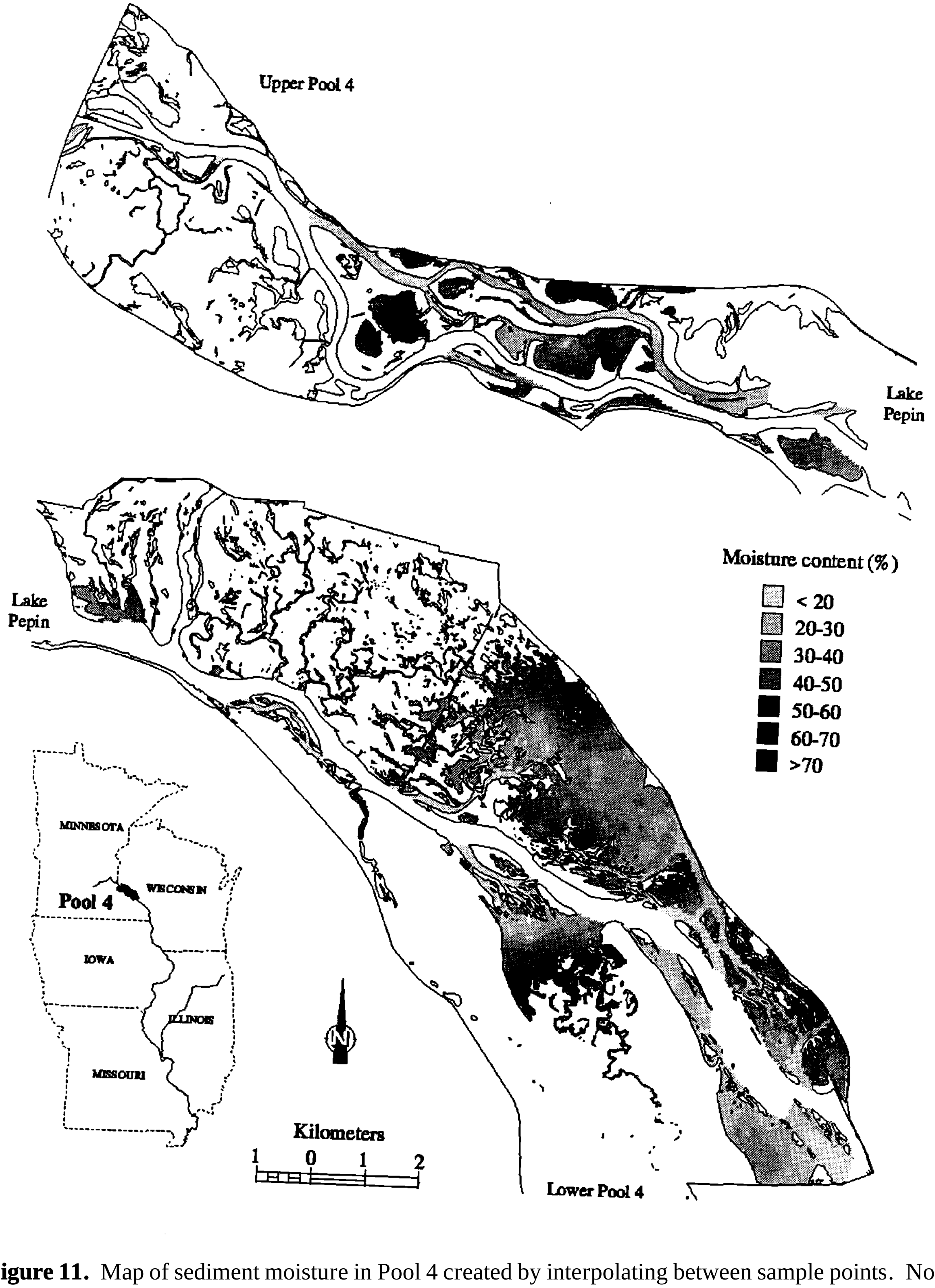


Figure 11. Map of sediment moisture in Pool 4 created by interpolating between sample points. Note that values were not interpolated in the main channel, main channel border, and Lake Pepin because those strata were only partly sampled.

REPORT DOCUMENTATION PAGE

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13. ABSTRACT (Maximum 200 words)

Moisture content, bulk density, and organic content of surficial sediments were estimated with a penetrometer in Navigation Pools 4 and 8 of the Upper Mississippi River during 1994 and 1995. Mean moisture content of sediment was low in both Pool 4 (39%, SD = 15.0%) and Pool 8 (34%, SD = 13.7%), suggesting that soft, fine sediments are uncommon in these pools. Sediment in much of the off-channel habitat was found to have similarly low moisture content. Sediment in small backwaters was particularly low in moisture content, although areas with sediment moisture content greater than 70% were found in small backwaters. Sediment in the large backwaters of Pool 4 was similar to sediment in the small backwaters of Pools 4 and 8, while in Pool 8 the large backwaters areas had sediment with a higher mean moisture content of 57% (SD = 14.8%). Only deep, dredged areas in Pool 8 were dominated by sediment with a high moisture content; here the mean moisture content was 67% (SD = 21.1%). The large, open water off-channel area in lower Pool 8 formed by impoundment had sediments similar to those of channel habitats. As a whole, sediment in off-channel habitats in Pools 4 and 8 had low moisture content, which suggests either small inputs of fine sediment or efficient transport of fine sediment through the off-channel habitats.

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The Long Term Resource Monitoring Program (LTRMP) for the Upper Mississippi River System was authorized under the Water Resources Development Act of 1986 as an element of the Environmental Management Program. The mission of the LTRMP is to provide river managers with information for maintaining the Upper Mississippi River System as a sustainable large river ecosystem given its multiple-use character. The LTRMP is a cooperative effort by the U.S. Geological Survey, the U.S. Army Corps of Engineers, and the States of Illinois, Iowa, Minnesota, Missouri, and Wisconsin.

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