2. Bathymetry - Chapter 2 extracted from James T. Rogala. 1999. Methodologies employed for bathymetric mapping and sediment characterization as part of the Upper Mississippi River System Navigation Feasibility Study. ENV Report 13. Interim Report for the Upper Mississippi River - Illinois Waterway System Navigation Study; prepared for U.S. Army Engineers District, Rock Island, U.S. Army Engineers District, St. Louis, and U.S. Army Engineers District, St. Paul.

Data Collection Strategy

Methods for generation of poolwide bathymetric data were established as part of the LTRMP mapping prior to the Navigation Feasibility Study. The LTRMP bathymetric data were intended to meet the needs of a variety of users. Details required within specific areas of interest (e.g., dredge sites) were not desired in this bathymetric coverage. Rather, the coverage was to represent pool-wide conditions representing bathymetry over a multi-year period. Interpolation between data points is used to generate a continuous surface of bathymetry for pool-wide coverages.

Several data types were used to generate the continuous surface of bathymetry. Most of the data was collected by a computerized hydrographic survey system. This was the desired method because of the rapid collection of data and accurate geographical positioning. However, land-based positioning survey systems are very inefficient in some cases. In particular, line-of-sight limitations of the land-based system require many transponder locations in narrow, forested channel areas. Collection of chart recordings along transects was used as an alternative method in these areas. Using information from the chart recordings, contours were hand drawn and then digitized. Another limitation of the automated survey systems is related to the use of soundings to determine water depth. Many of the aquatic areas within the pools are shallow and highly vegetated nearly year-round, and accurate acoustical soundings are difficult to obtain under these conditions. To obtain water depth data in these areas, manually measuring water depth with a sounding pole is required. These spot measurements can be used effectively because these areas are small and have little slope.

Two other types of data were used to assist in the interpolation of the coverage. An existing GIS land/water boundary and assigned water depths based on the location in the pool were used to provide the data needed to interpolate between sounding data and the shoreline. Without these data on the shoreline, extrapolation of values beyond data points would often yield undesirable results. The interpolation to the shoreline was needed because the bathymetric surface was desired to cover all aquatic areas within a pool. The second type of data used to assist in the interpolation of values was break-line data. Break-line data add data points interpolated along individual lines based only on actual data that intersect the line. Break-line data are typically added to maintain slopes and linear features between selected data points where data were sparse. Further discussion on shoreline data and break lines is included in this report in the sections on data collection and GIS database generation.

Automated System Configuration

Many hydrographic survey equipment manufacturers have integrated hardware and software into an automated survey system to enable rapid collection of digital geographical positions and depth data. There are three basic components of an automated survey system: a geographical positioning device, a depth sounder/digitizer, and a computer to integrate and store data. The LTRMP has used three survey systems through acquisition and replacement of various components of systems.

In 1988, the first system was acquired from Ross Laboratories of Seattle, WA (Ross Laboratories 1988). This system uses a land-based positioning system. The system computes a position using distances to surveyed locations obtained from a microwave positioning system. The theory behind microwave positioning is discussed in the operator's manual for the system (Del Norte 1986). Typically, four remote transponders are set out at known geographical locations to provide distances to the master transponder on board the survey vessel (Figure 1). The microwave positioning system relies on line-of-sight communication between the master transponder and remotes and typically provides distances accurate to 1 m (3 ft). Positions are calculated using the distances to the known locations in a least squares estimate. Accuracy of positions is dependent on number of transponders used, the geographical arrangement of the transponders, positional accuracy of the transponder locations, and the quality of the signals received.

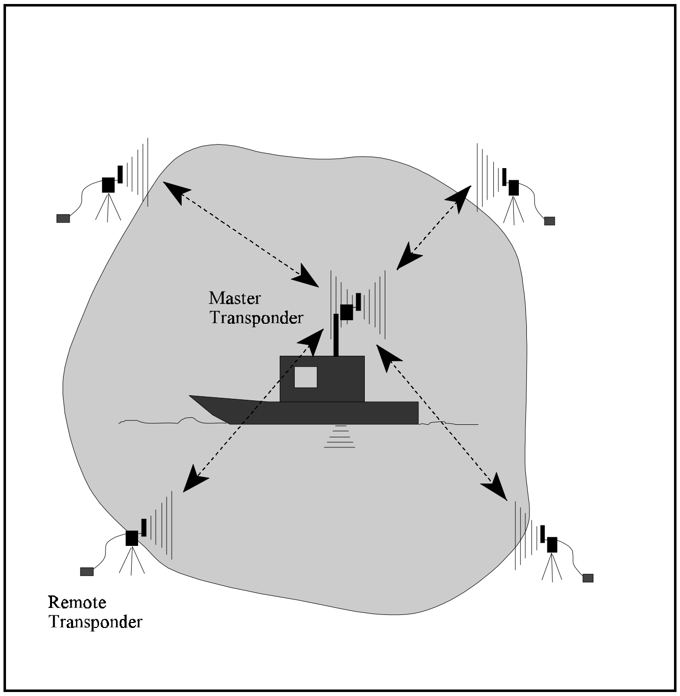

Figure 1. Schematic of land-based positioning survey system

The computer software merges the calculated position with a digitized sounding of depth obtained from a depth sounder/chart recorder. A minimum digitized water depth of 0.79 m (2.6 ft) is obtainable with this system, and depths are recorded to the nearest 0.03 m (0.1 ft). Nominal accuracy is dependent on depth, with shallow survey accuracy as low as ± 0.03 (0.1 ft) and less accurate recordings of ± 0.12 m (0.4 ft) for deeper surveys. Other errors during soundings may decrease accuracy of recorded depths. The merged position and depth data are recorded on a computer disc for postprocessing in the office. The majority of the data used to generate poolwide maps for Pools 4, 8, 13, and 26 was collected with this system.

The LTRMP acquired a second automated survey system in 1993 to incorporate Global Positioning System (GPS) technology into LTRMP bathymetric surveys. General information on the theory of GPS is provided in the manual for the GPS unit (Starlink 1997). Because GPS is a satellite-based positioning system, it greatly reduces field surveys by eliminating the need for surveyed locations for transponders.

The system was acquired from Innerspace Technology, Inc. (1994), Waldwick, NJ. It includes a two-channel GPS system that can achieve differential GPS. Differential GPS reduces the error by using additional data from a reference GPS receiver at a known position to correct positions obtained during surveys. The position data have an accuracy of <1 m two-dimensional Root Mean Square (2DRMS). The reference stations of the U.S. Coast Guard Beacon system (Figure 2), which has became operational along the entire UMRS, are used. The beacon system transmits signals for performing corrections in real-time; therefore, no postprocessing for corrections is necessary. Position data are used in a manner similar to that described previously for the land-based positioning system. A new depth sounder/digitizer was also obtained that allows for shallow-water surveys to depths of 0.5 m (1.7 ft) with accuracy similar to the previously used sounder. This system was used to conduct surveys in the LaGrange Pool and to collect the systemic transect data.

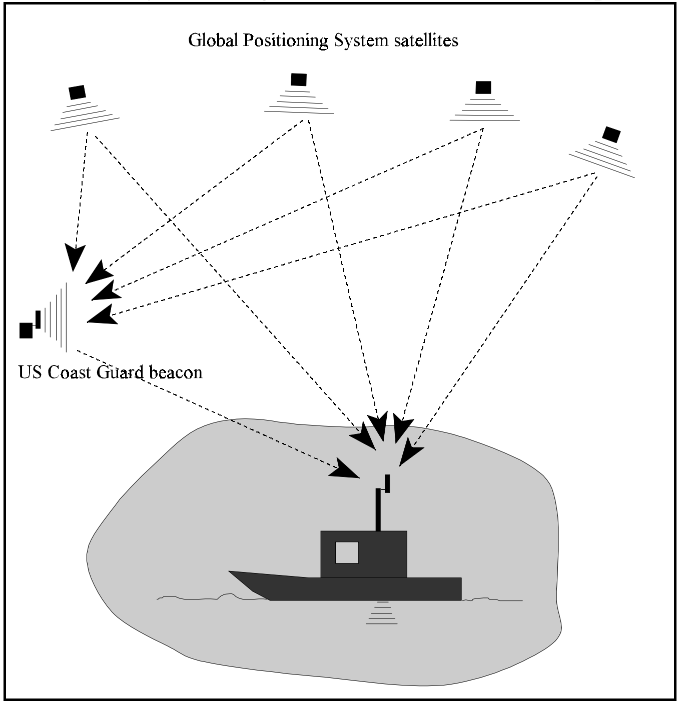

Figure 2. Schematic of GPS positioning survey system

In 1997, the LTRMP acquired several new components for the survey system: a new 12-channel GPS receiver and beacon signal receiver and new software from Coastal Oceanographics, Inc. (1995), Middlefield, CT. The accuracy is similar to that of the previous GPS unit (<1 m 2DRMS), but the increased number of channels provides for better tracking of satellites under conditions of signal interference. The new software, Hypack, is a more user-friendly Windows application. The Hypack software improves the efficiency of data collection by allowing the boat operator to display shoreline data and maps of previously collected bathymetry data while collecting data. The Hypack system was used to collect data in the LaGrange Pool. Specifications for all three systems are included in Appendix A.

Data Collection

The data collection procedures described in the following paragraphs are meant to be used in conjunction with the user's manuals for the three software packages (Ross Laboratories 1988; Innerspace Technology 1994; Coastal Oceanographics 1995) used by the LTRMP bathymetric survey component. The general procedures presented here were written specifically for the type of work performed by the LTRMP. Although specific language and procedures differ among the three software packages, the methods are somewhat similar. The methods given here use generic text and a common language to describe the three different procedures.

In preparation for conducting surveys, geographical boundaries were established for each survey. The boundaries were based on manageable size of files, acceptable geometry of transponders for range positioning systems, and river mile lengths to simplify adjustment to the reference water surface elevation. Reference transect lines and line spacing intervals were established (Figure 3). These transect lines were displayed during the survey to assist the boat operator in navigating along lines where data collection is desired. For the Hypack system, background coverages such as shorelines are brought into the system as DXF files.

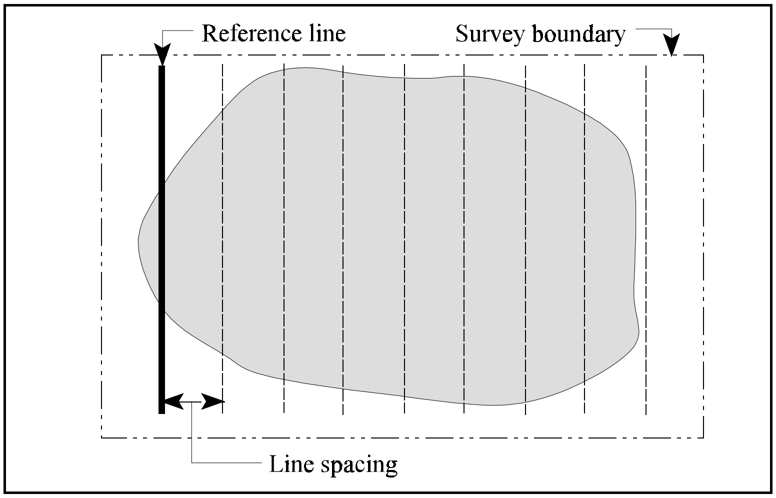

Figure 3. Schematic of parameters used to set up a survey

Before data were collected with the depth sounder, the sounder was calibrated to account for variability in water quality parameters. The calibration was performed by anchoring the boat over a location with a bottom of uniform depth. The water depth was acquired with a calibrated sounding pole. With the sounding equipment on, the speed of sound was adjusted until the digitized depth equaled the measured water depth. This calibration was performed at a water depth similar to the mean water depth within the survey area. For example, if a survey was conducted only within shallow backwaters, then the calibration was performed within the shallow backwater. This adjustment of the speed of sound accounts for variability in water quality parameters that affect the speed of sound in water, which is needed to calculate distance (water depth) based on the travel time of the reflected pulse.

To initiate a survey, the survey setup and a reference line were selected. When a line was started, the automated survey system began data collection by recording geographical positions and depths in computer data files as the survey boat was operated along the transect line. The chart recorder was turned on whenever digital data were acquired to generate a hard copy profile of the soundings. Distance off the transect line (offset) and distance along the transect line were displayed on the boat video display to guide the boat operator. For the systemic 1.6-km (1-mile) transects, each transect was established as a reference line and no data were collected other than along reference lines. For poolwide mapping, data were collected along offsets from the reference line, either as transects spaced along the selected spacing interval or “free-form” lines based on the offset displayed.

For the poolwide mapping, the track line arrangement used differed depending on the type of aquatic area, as defined by Wilcox (1993), where the survey was conducted. Main channel, side channel, and backwater areas were surveyed using a combination of different types of track lines (Figure 4). In the main channel, north-south and east-west track lines were surveyed at regular intervals over the entire area. Track lines were 61 m (200 ft) apart on the lines most parallel to the flow and 152 m (500 ft) apart on the lines most perpendicular to the flow. Data were also collected along the shorelines at two or three distances offshore. When structures (i.e., wing dams) were present, data were collected along two or more lines above, two or more lines below, one line on top of, and four to eight lines across the structure. Side channel track lines included one or more shoreline runs, lines run approximately 61 m (200 ft) or less apart perpendicular to the flow, and a line along the thalweg. Data collection in backwaters included track lines on north-south or east-west lines at 61-m (200-ft) intervals, lines at one or two distances from the shoreline, and channel type track lines in channels if they existed within the backwater.

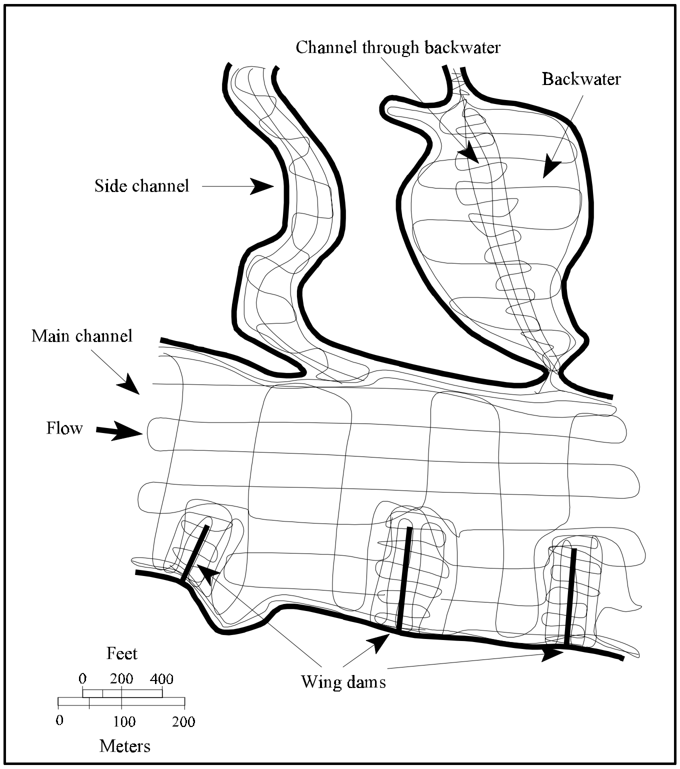

Figure 4. Typical arrangement of track lines for various aquatic area types

Data were collected within the survey area until the desired coverage was obtained, as described previously. Areas with depths less than the minimum depth limit of the digitizer were avoided. The recorded files contained geographical position and depth data in a series of x-, y-, and z-values. A record was obtained every 0.33 to 1.5 s, depending on the system and the setting of the time interval in some software. Point data density along track lines was dependent on boat speed, and data points usually ranged between 3 and 9 m (10 and 30 ft) apart. Hard copies of depth soundings in the form of chart recordings of the profile data along the track line were labeled with the survey name and line number. Line numbers increased by one each time a new line was started. These chart recordings are used during editing to evaluate potential errors in digital recordings of depths.

In addition to the automated data collection, data were collected by chart recordings along transects where automated collection was not efficient with the land-based positioning system. Shore-to-shore transects were selected to provide adequate information to hand-draw contours. Typically, transects were spaced farther apart than those of the automated survey because contours were hand drawn rather than computer interpolated. Calibration of the depth sounder was performed daily prior to surveying, as described previously. A transect location was selected and drawn on copies of aerial photography (1:15,000 natural color) in the field. The boat then traversed the transect at a constant speed while the chart recorder was running. The distances to the shore at the beginning and end points were recorded, as well as the direction of the transect.

Manual water depth measurements using a calibrated sounding pole were collected to fill in gaps in the coverage of data from other sources. Locations for measurement were selected using a GIS by displaying locations of actual data points collected with other methods. The x- and y-coordinates of the selected locations and maps of the locations were produced in the GIS. Using the field maps and a real-time differential GPS unit, the survey crew navigated to each of the selected locations and obtained a water depth reading to the nearest tenth of a foot. Data were entered into a computer spreadsheet.

Data Editing

All water depth data were adjusted to a constant reference water surface elevation for each navigation pool. This was necessary because surveys collected water depth data at varying water levels. The use of a constant reference elevation for each pool provided for easy conversion of depth data to elevation data referenced to the National Geodetic Vertical Datum (NGVD), which is the most commonly used reference surface. The water surface elevations for each pool are in feet above mean sea level, with an

NGVD of 1912 for the St. Paul and Rock Island District portions of the Mississippi River and an NGVD of 1929 for the St. Louis District portion of the Mississippi River and all of the Illinois River.

The selection of the reference water surface elevation was based on pool elevations used by the USACE. However, the three districts (St. Paul, MN, Rock Island, IL, and St. Louis, MO) in the UMRS use different methods for establishing reference elevations for bathymetric surveys. Only the Rock Island District uses a method of constant water surface elevation within each pool, which is referred to as flat pool elevation. The LTRMP has adopted this method and uses the USACE flat pool elevations as provided in the Master Reservoir Regulation Manual (U.S. Army Engineer District, Rock Island, 1981) for reducing depth data to a reference water surface elevation in the Rock Island District.

Methods in the other two districts were modified to obtain flat pool elevation values. In the St. Paul District, the project pool elevation (maximum lowest controlled pool elevation), as described in the Master Regulation Manual (U.S. Army Engineer District, St. Paul, 1969), for most pools is used as the reference water surface elevation. The exception is Pool 7, for which an elevation of 638.5[1] is used as the flat pool elevation to match the water surface elevation used for hydrographic surveys within the St. Paul District. Similarly, the greatest minimum pool stage used for hydrographic surveys by the St. Louis District is used as the reference water surface elevation in Pools 24, 25, and 26. These elevations differ slightly from the elevations reported in the Master Water Control Manual (U.S. Army Engineer District, St. Louis, 1980) for those pools. The flat pool reference elevations used by the LTRMP for each pool in the UMRS are included in Table 1.

Table 1
Water Surface Elevations Used as Flat Pool Depths

Pool	Elevation	Pool	Elevation	Pool	Elevation
1	725.1	13	583.0	Brandon Road	538.5
2	687.2	14	572.0	Dresden Island	504.5
3	675.0	15	561.0	Marseilles	483.2
4	667.0	16	545.0	Starved Rock	458.7
5	660.0	17	536.0	Peoria	440.0
5A	651.0	18	528.0	La Grange	429.0
6	645.5	19	518.0	Alton	419.0
7	638.5	20	480.0		
8	631.0	21	470.0		
9	620.0	22	459.5		
10	611.0	24	449.1		
11	603.0	25	434.2		
12	592.0	26	418.5		

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[1] To convert elevations given in feet to meters, multiply by 0.305.

In most cases, water surface elevation for a survey site on the day of the survey was estimated by linear interpolation between elevations from USACE main channel gauges above and below the survey as illustrated in the equation:

$$\mathrm{swse} \quad \mathrm{dwse} \quad (\mathrm{srm} - \mathrm{drm})\ [(\mathrm{uwse} - \mathrm{dwse})/(\mathrm{urm} - \mathrm{drm})] \tag{1}$$

where

swse = survey water surface elevation

dwse = downstream gauge water surface elevation

srm = survey river mile

drm = downstream gauge river mile

uwse = upstream gauge water surface elevation

urm = upstream gauge river mile

These estimates of water surface elevations were more accurate at low-water conditions than at high-water conditions, particularly for contiguous off-channel areas farther from the main channel. However, a more accurate estimate of water surface elevation was obtained during high-water surveys by setting a temporary gauge near the survey area. The elevation of the gauge was then later approximated during relatively flat pool conditions when the slope of the water surface was nearly linear, thus providing a better estimate of the water surface elevation at the time of the survey. Nonetheless, linear interpolation of water surface elevations provides a source of error because the water surface slopes between gauges is often nonlinear.

The adjustment to flat pool was calculated by subtracting the water surface elevation on the day of the survey from the flat pool elevation for the pool where the survey was located. In most cases, a single adjustment value was used for the entire survey. However, if the survey extended over many miles during high water surface elevation slope conditions, then several adjustment values were used along the length of the survey. After water depth data were adjusted to the reference water surface elevation, negative depths representing height above the reference elevation sometimes resulted for surveys conducted in very high water. These negative depths represent nearshore or terrestrial areas.
Errors in both geographical position and water depth can occur during data collection. Positional errors generally occur due to loss of suitable communication with remote transponders or satellites. Errors in depth soundings occur when interference by something in the water column (i.e., fish, turbulence) causes a return signal or loss of signal prior to the signal reaching the river bottom. Errors are detected by plotting the positions or depths in 2-D (Figure 5).

Data collected with the Ross system were edited with the Ross editing software (Ross Laboratories 1988) by altering positions or depths of errant data. Position data were edited by either using a smoothing function or altering x- and y-coordinates. A smoothing function efficiently corrects “spiked” position errors without manually altering x- and y-coordinates. However, the smoothing function was used only on lines where observed errors could be corrected without altering positions of other data points along the line. Errant depths were detected by a screening process that identifies large changes in depths at adjacent positions. These depths were changed if the chart recordings verified that the depth was truly an error. No records were deleted while editing using the Ross software.

The Innerspace and Hypack data were edited in a GIS using a menu-driven program written in Arc Macro Language (AML) for Arc/Info (Environmental Systems Research Institute, Inc. (ESRI) 1991a). In contrast to the Ross editing package, the GIS editing program allows only deletion of errant records, and no smoothing of the position data is performed. Using the Arcedit module of Arc/Info (ESRI 1991b), the depths are displayed as illustrated in Figure 5. Errant depths are identified by visual observation and confirmed by comparison with the chart recording. Those depths in error are selected and deleted. Similarly, positions are plotted and errant positions are selected and deleted.

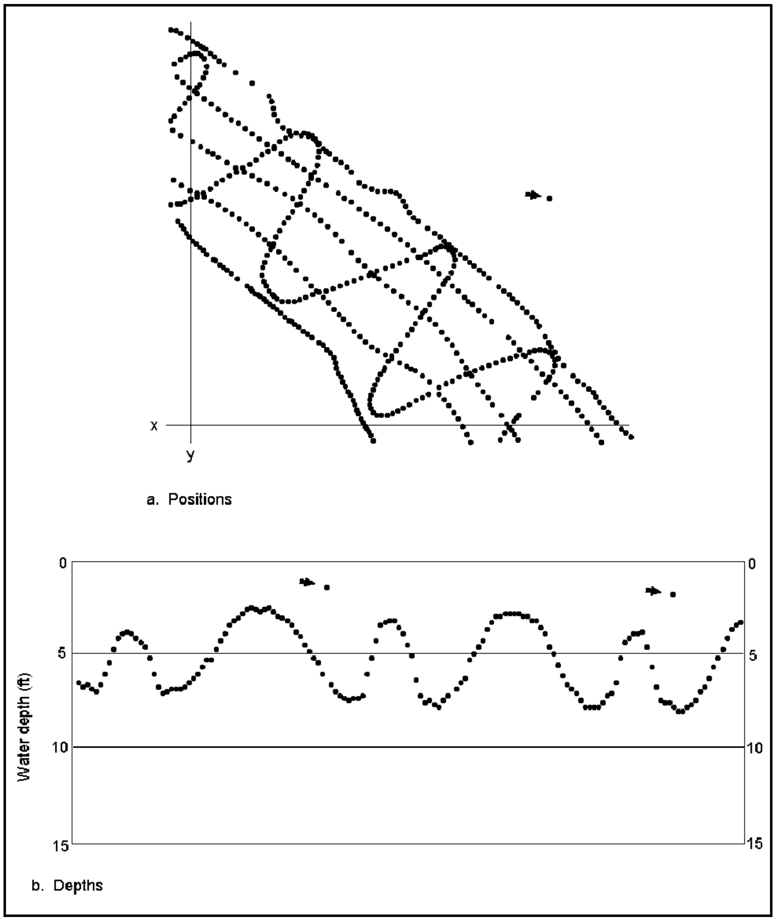


Figure 5. Plots of data used to edit errors in positions and depths. Arrows identify points to be edited.

GIS Database Generation

Both the poolwide coverage and the systemic transect data were transformed from the various data types to a GIS coverage in Arc/Info. For the systemic transects, which were collected only with an automated system, the method was simply to output the automated survey system data into an ASCII file containing records of x- and y-coordinates and water depth. A point coverage was generated from an ASCII file after the file was reformatted into the format required by the Arc/Info GENERATE command.

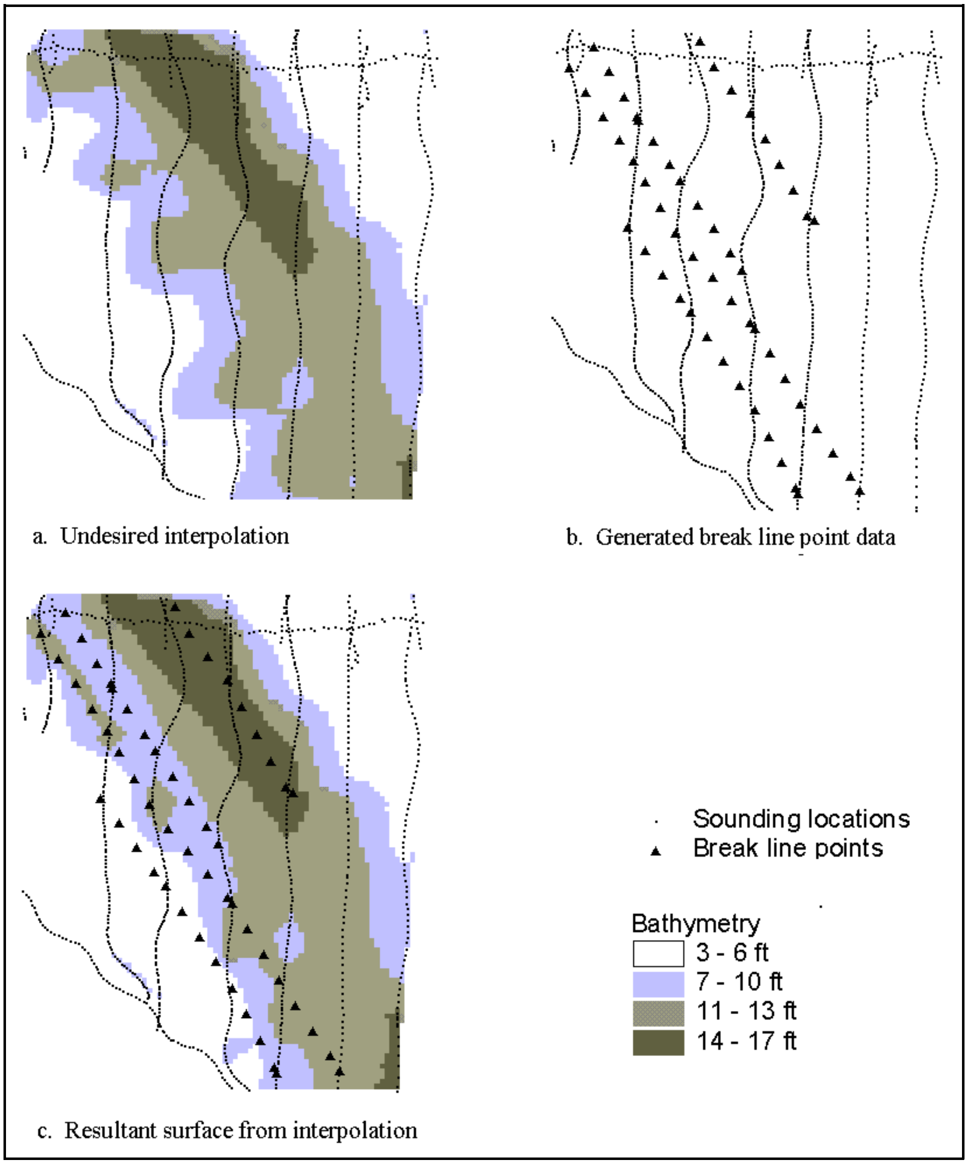
The generation of Arc coverages from the files was automated by a menu-driven AML program. The systemic transect data were not altered geographically by editing positions of points to fit existing GIS land cover data; therefore, some points may overlay with land rather than water.

Arc/Info coverages were also generated from ASCII files for some data types used to generate a poolwide coverage. The automated system data and the spot elevation survey data were converted to Arc point coverages. Points in these coverages were compared to the GIS coverage of land/water and positions altered to assure that water depths occurred in aquatic areas. The shoreline data were obtained from an existing Arc polygon coverage of photo-interpreted land cover types by grouping aquatic and terrestrial land cover types. Water depth of the shoreline was determined by interpolating between USACE gauge readings on the date of the photography as described previously. The shoreline arcs were split at each river mile, and the interpolated shoreline depth for each river mile was assigned to the arcs. The photography was collected in low-water conditions, so the interpolated shoreline depths were near flat pool condition and therefore nearly linear. This minimized the potential for error as a result of linear interpolation of the water surface elevation.

The contours drawn from hydrographic chart recordings were digitized directly to create Arc/Info line coverages and attributed with the contour water depth. Base maps of shorelines at a scale of 1:4,800 or larger were created for survey areas. The transect location was transcribed from the aerial photo to base maps. Distances of the nearshore portion of each transect that was not surveyed were scaled off, leaving the remaining distance across the transect equaling the distance of the chart recording. The depths that were used to draw contours on the chart recording were then marked, and their location plotted on the base map by scaling the distance across the transect. Contours were drawn on the base map on the basis of depth locations plotted along the transects. Contours were digitized and georeferenced using identifiable locations on the shoreline for which coordinates were acquired from the GIS shoreline coverage. Adjusting contour depths to the reference water surface elevation was done either prior to or after drawing contours.

A triangulated irregular network (TIN) was used to generate an initial surface of water depth. The TIN is a set of adjacent, nonoverlapping triangles created using Delauney triangulation between the data points (ESRI 1991c). Data points from the automated system surveys and spot elevation surveys were used along with data points for vertices of the contour and shoreline arcs. All data were projected into a common projection of Universal Transverse Mercator Zone 15. Vertices along the arcs were placed at an interval of between 5 and 10 m to increase the number of data points the contours provided to the surfacing procedure. Some reduction of data was done by setting a minimum proximity between data points to 1 m. A TIN was created, and then a raster coverage was interpolated for 2-D viewing.

The raster coverage was displayed and examined for problem areas. The problems were generally associated with the insufficiently dense data to maintain slopes, such as in submerged channels and nearshore areas. To maintain the correct slope, break lines were added to the problem areas (Figure 6).


a. Undesired interpolation

b. Generated break line point data

c. Resultant surface from interpolation

Figure 6. Example of the undesirable interpolation, break line point data generated to maintain the channel slope, and resultant surface from interpolation with the break line data added

Break line data were generated from an AML program written to interpolate values for regularly spaced points along lines based on the data that intersected the lines (Figure 7). The lines were added as arcs traversing the problem areas. The break line points of water depth were included in the creation of a TIN, along with the four types of data described previously. A new TIN and raster coverage were

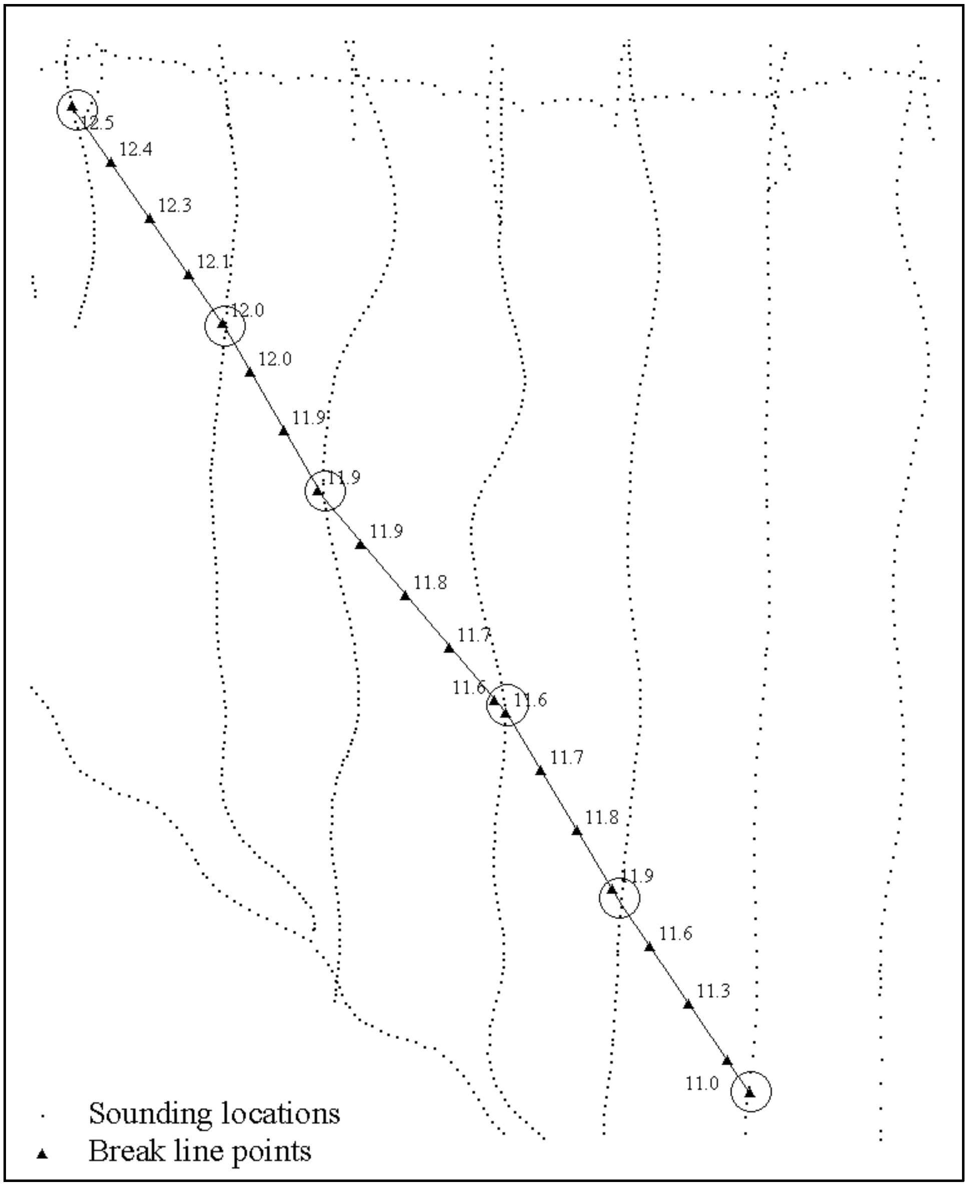


Figure 7. Example of values interpolated along a break line based on the depth values that intersect the line (circled)

created for review and additional break lines added, if needed. This process was repeated until no obvious problem areas were found in the raster coverage.

The interpolation of an Arc/Info GRID raster coverage from the TIN surface included several processes. First, a lattice of points was generated by linear interpolation between the nodes of the TIN surface. The depth values in the resultant lattice contained more significant figures than the collected data could justify. Therefore, the vertical resolution of the lattice was reduced to better match the significant places beyond the decimal place of the recorded depths. A unit of centimeters was selected for depth because it adds one place to the tenths of feet collected during surveys. In the process of reduction, the lattice was converted to an integer GRID coverage, which is a more efficient method of data storage. Because the GRID coverage included data extrapolated in areas beyond the actual data, the spatial coverage of the GRID coverage was reduced by using a land/water grid to eliminate elevation data in nonaquatic areas. In addition, data were insufficient for reasonable interpolation of depths in some aquatic areas. Values in the bathymetry grid were replaced in these areas with a unique value to represent the unreliable interpolated values.

A related GRID coverage was generated by filling cells of a GRID coverage where actual data were located. The cells were filled with values representing the source of data (e.g., automated surveys, break lines) used in the TIN. This coverage can be used to assess the spatial density of data used to generate the bathymetric GRID coverage. Errors in the interpolated values can be generally assessed by evaluating the gaps between data and the heterogeneity of the depths of adjacent data points.

The data in the final grid coverage included items with depth expressed in meters and feet below flat pool elevation. These data can be transformed into feet above mean sea level by subtracting the water depth from the flat pool elevation. Flat pool elevations for each pool were reported previously in the "Data Editing" section of this chapter.

References

Coastal Oceanographics. (1995). " Hypack user’s manual," Coastal Oceanographics Inc., Middlefield, CT.

Del Norte. (1986). " Operation/service manual, Model 217E/218E Microwave Transponder," Del Norte Technology, Inc., Euless, TX.

Environmental Systems Research Institute, Inc. (1991a). " Arc/Info User’s Guide 6.1, AML user’s guide," Redlands, CA.

Environmental Systems Research Institute, Inc. (1991b). " Arc/Info User’s Guide 6.1, Editing coverages & tables with Arcedit," Redlands, CA.

Environmental Systems Research Institute, Inc. (1991c). "Arc/Info User’s Guide 6.1, Surface modeling with TIN," Redlands, CA.

Headquarters, U.S. Army Corps of Engineers. (1994 (31 Oct)). " Hydrographic surveying," EM 1110-2-1003, Washington, DC.

Innerspace Technology. (1994). " Innerspace Technology portable hydrographic survey system operating manual," Waldwick, NJ.

Ross Laboratories. (1988). " Dolphin Survey System Single Track Software Programs Operator's Manual," Seattle, WA.

Starlink. (1997). " User’s manual, DNAV-212 GPS receiver with dual channel MSK beacon receiver," Austin, TX.

U.S. Army Engineer District, Rock Island. (1981). " Master reservoir regulation manual for Mississippi River, nine foot channel navigation project," Rock Island, IL.

U.S. Army Engineer District, St. Louis. (1980). " Master water control manual for Mississippi River, nine foot channel navigation project," St. Louis, MO.

U.S. Army Engineer District, St. Paul. (1969). " Master regulation manual for Mississippi River, nine foot channel navigation project," St. Paul, MN.

Wilcox, D. B. (1993). "An aquatic habitat classification system for the Upper Mississippi River System," EMTC 93-T003, U.S. Fish and Wildlife Service, Environmental Management Technical Center, Onalaska, WI.

Appendix A

Components of Long Term Resource Monitoring Program (LTRMP) Hydrographic Survey Systems

Dolfin Survey System by Ross Laboratories, Seattle, WA

Ross Laboratories Survey system: Model 5001 recorder, Model 4401 transceiver, Model 6801 digitizer, 200-kHz 3.5-deg transducer, steering indicator

Del Norte 542 Trisponder System: Model 542 digital distance measuring unit, Model 217E master transmitter/receiver with 360 × 19 antenna, Model 217E remote transmitter/receiver with 110 × 7 antenna(4)

HP9000 Model 520 computer

Ross Dolfin System software

Portable Hydrographic Survey System by Innerspace Technology, Inc., Waldwick, NJ

Model 448 Thermal Depth Sounder Recorder with 208-kHz 3-deg transducer, Model 603 Remote Indicator

Model 610 REF Motorola 620 System Interface GPS Receiver with Starlink MRB-2A MSK beacon receiver

486DX computer with EGA display

ITI Field/Office software

Hypack Survey System by Coastal Oceanographics, Middlefield, CT

Model 448 Thermal Depth Sounder Recorder with 208-kHz 3-deg transducer

Starlink DNAV-212G/MBA-2 – 1-m 2DRMS accuracy integrated 12-channel DGPS and 2-channel automatic MSK beacon receiver

Dell Latitude LM M166MMX Notebook with Windows 95

Hypack Lite Hydrographic Survey Software