Methods for Assessing Sedimentation in Reservoirs

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Introduction
Sediment accumulation and other factors continue to create water quality problems that affect the many uses of Kansas reservoirs. The most pressing issue is ensuring the quality of drinking water supplies. Flood control, recreation, irrigation, and other reservoir uses also must be protected, and renovation to ensure reservoirs’ long-term viability is becoming increasingly necessary. Solving these problems is an enormous challenge that requires gathering crucial information about physical, chemical, and biological conditions in reservoirs and watersheds. Bathymetric (lake bottom contour) mapping and reservoir assessments are becoming particularly important as federal, state, and local agencies contemplate and initiate sediment management projects to renovate Kansas reservoirs.

Current State of the Science: Bathymetric Mapping

Traditional Approaches to Water Depth Measurement
Information on water depth has been important for thousands of years. Until the 20th century, water depth measurements were obtained manually from the side of a boat with a sounding line and lead weight (Figure 1) or, in shallower waters, a pole with depth markings. Sounding weights and poles often were tipped with an adhesive substance, such as wax or lard, to capture a sample of sediment. The location of each sounding (depth measurement) was determined by estimation or direct measurement in smaller water bodies or harbors and by celestial navigation (sextant or astrolabe) in oceans. Thus, horizontal accuracy

Figure 1. A 19th century sounding boat
Image from NOAA Central Library
of these ad-hoc spot positions generally was low. A measure of control could be imposed in areas where range lines could be established between identifiable landmarks on shore. This permitted repeat visits to sounding positions over time to monitor sedimentation or erosion.

Manual approaches to depth measurement are labor intensive, have relatively low accuracy and precision, and have considerable limitations, particularly for mapping detailed bottom contours or estimating whole-lake sedimentation volumes, rates, and changes. Development of acoustic echosounding systems that use global positioning systems technology for horizontal position location enabled “whole-lake” approaches that build detailed representations of depth contours based on mathematical interpolation of thousands of geographically referenced depth measurements.

Whole-Lake Acoustic Echosounding for Lake Depth (Bathymetric) Mapping

By the 20th century, advances in acoustic science and technology permitted development of sonar systems, originally used for military purposes but adapted for civilian mapping operations. During the past decade, acoustic echosounding systems became sufficiently self-contained and portable, allowing for use even on small lakes and ponds.

Acoustic echosounding relies on accurate measurement of time and voltage. A sound pulse of known frequency and duration is transmitted into the water, and the time required for the pulse to travel to and from a target (e.g., a submarine or the bottom of a water body) is measured. The distance between sensor and target can be calculated using the following equation:

\[ D = \frac{1}{2} (S \times T) \]

Where \( D \) = distance between sensor and target, \( S \) = speed of sound in water, and \( T \) = round-trip time.

To acquire information about the nature of the target, intensity and characteristics of the received signal also are measured. The echosounder has four major components: a transducer, which transmits and receives the acoustic signal; a signal generation computer, which creates the electrical pulse; the global positioning system, which provides precise latitude/longitude coordinates; and the control and logging computer. Typical acoustic frequencies for environmental work are:

- 420 kHz – plankton, submerged aquatic vegetation
- 200 kHz – bathymetry, bottom classification, submerged aquatic vegetation, fish
- 120 kHz – fish, bathymetry, bottom classification
- 70 kHz – fish
- 38 kHz – fish (marine), sediment penetration

Prior to conducting a bathymetric survey, geospatial data (including georeferenced aerial photography) of the target lake are acquired, and the lake boundary is digitized as a polygon shapefile. Transect lines are predetermined based on project needs and reservoir size. Immediately before or after the bathymetric survey, elevation of the
lake surface is determined. For large reservoirs (e.g., U.S. Army Corps of Engineers or Bureau of Reclamation lakes), elevation is determined using local gages. For smaller reservoirs that are not gaged, a laser line is established from a surveyed benchmark to the water surface at the edge of the lake.

System parameters are set after boat launch and echosounder initialization. Water temperature at a depth of 1 to 2 meters is recorded (°C) and used to calculate the speed of sound in water for the given temperature and depth. A ball check is performed using a tungsten-carbide sphere, which is supplied specifically for this purpose with each transducer. The ball is lowered to a known distance below the transducer face. The position of the ball in the water column (distance from the transducer face to the ball) is clearly visible on the echogram, and the echogram distance is compared with the known distance to ensure parameters are set properly.

A typical survey procedure for smaller lakes is to run the perimeter of the lake, maneuvering as close to shore as permitted by boat draft, transducer depth, and shoreline obstructions to establish near-shore lake bottom dropoff. Then, predetermined transect patterns are followed, and data are automatically logged by the echosounding system.

Raw acoustic data are processed through proprietary software to generate ASCII point files of latitude, longitude, and depth. Point files are ingested to ArcGIS and merged into a master point file, and bad points and data dropouts are deleted. Depths are converted to elevations of the lake bottom based on the predetermined lake elevation value. Lake bottom elevation points are interpolated to a continuous surface by generation of a triangulated, irregular network or simple raster interpolation. Elevation of the digitized lake perimeter is set to the predetermined value and used in the interpolation as the defining boundary of the lake. Then, area-volume-elevation tables can be computed from the lake bottom surface model.

**Current State of the Science: Sediment Classification and Thickness Assessment**

**Acoustic Characterization of Sediment Types**

The acoustic echosounding system has a proprietary software suite that classifies reservoir bottom sediment (e.g., rock, sand, silt, or mud) based on characteristics of the acoustic return signal (Figure 2). Ideally, this process would be used to collect acoustic data from known bottom types to provide a "library" of Kansas-specific classification data. Sediment sampling and coring also provide bottom composition data for calibration and accuracy assessment.

![Figure 2. Acoustic signal classification for bottom type mapping](Image courtesy of Mark Jakubauskas, Kansas Biological Survey)
Approaches for Estimating Sediment Thickness

Estimating thickness of accumulated sediment in a reservoir is not a simple process. Three techniques—sediment coring, topographic differencing, and acoustic estimation—show promise for estimating the spatial distribution, thickness, and volume of accumulated sediment in Kansas reservoirs. Each technique has strengths and limitations, and an ideal methodology uses all three approaches in concert to calibrate and cross-check results.

Sediment Coring. Sediment cores typically are taken from a boat using a gravity corer or vibrational coring system. In either case, an aluminum, plastic, or steel tube is forced into the sediment, ideally until pre-impoundment substrate is reached. The tube is withdrawn and sliced longitudinally, or the sample is carefully removed from the tube, allowing for sediment thickness measurement and sample collection. The interface between pre-impoundment substrate and post-impoundment sediment is fairly distinct in Kansas lake sediment samples (Figure 3).

Several companies manufacture and distribute sediment coring systems. However, most systems are intended for deep water marine use in the ocean and are not suitable for smaller, shallower lakes and reservoirs. Sampling inland reservoirs requires a portable, self-contained unit with an independent power supply that is small enough to fit on an outboard motorboat or pontoon boat, which disqualifies pneumatic, hydraulic, or high-voltage systems commonly used on larger marine vessels. Smaller systems have been developed and are used in Kansas (e.g., the VibeCore System, Specialty Devices Inc., Texas).

Figure 3. Sediment core from Mission Lake in Brown County, Kansas, showing pre-impoundment substrate (left) and post-impoundment sediment (right)
Photo courtesy of Kansas Biological Survey
A benefit of the sediment coring approach is that cored material can be preserved and analyzed for sediment classification or chemical composition. However, core sampling is time and labor intensive; only a small number (≈10 to 25) of point samples can be taken per day. Although sediment core data are likely highly accurate for a given location, the overall result is an incomplete and fragmentary representation of sediment thickness and volume across the reservoir.

**Topographic Differencing.** The topographical approach computes the difference between pre-impoundment and present-day lake bottom topographic data and uses that information to create a spatially-explicit, three-dimensional representation of sediment accumulation (Figure 4). Data from archived topographic maps, reservoir blueprints, or “as-built” pre-impoundment topographic surveys are used to create a pre-impoundment surface, and data from new bathymetric surveys are used to create a map of current reservoir bottom topography. Unlike spot measurements of sediment thickness, topographic differencing can display a “whole-lake” representation of sediment accumulations, facilitating estimates of sediment volume (Figure 5).

However, quality of sediment thickness data produced by this approach depends on quality of data used to create pre-impoundment maps. Archival topographic data can have one or more of the following limitations: no information on horizontal or vertical projection of data used, referenced to an arbitrary local elevation (i.e., non-standard/nongeodetic vertical control), or of inappropriate spatial scale to produce meaningful comparisons with present-day topographic data.

![Figure 4. Topographic differencing of pre-impoundment and present-day reservoir topography](image-url)

Left: 1923 engineering contour map of Mission Lake in Brown County, Kansas. Center: Digital elevation model created from 1923 map. Right: Present-day lake bottom topography created from analysis of acoustic echosounder data. Images courtesy of Kansas Biological Survey.
Acoustic Estimation. In the acoustic approach, high-frequency and low-frequency transducers (200 kHz and 38 kHz) are operated simultaneously during a lake survey. Differencing acoustic returns from high and low frequencies (reflecting off the current reservoir bottom and the pre-impoundment bottom, respectively) have shown considerable promise for successful sediment thickness mapping in inland reservoirs (Figure 6; Dunbar et al., 2000).

Our results indicate that mapping the base of sediment acoustically works best in reservoirs that are dominated by fine-grained deposition (clay and silt, rather than silt and sand). Reservoirs with fine-grained-deposition fill from the dam towards the backwater and no delta forms at the tributary inlet. As long as the water depth is greater than the sediment thickness, the base of sediment can be mapped without interference from the water-bottom multiple reflection, and the entire reservoir can be surveyed from a boat. Coarse-grained dominated reservoirs fill from the backwater towards the dam and form deltas in the backwater. In the time [sic] the backwater region cannot be surveyed, because it is dry land. In these cases, the only option is differing the bathymetry. (John Dunbar, personal communication, 2007)
Figure 6. Echograms of acoustic reflectance at multiple frequencies for reservoir sediments:
a) High frequency, showing strong discrimination of sediment-water interface; b through e) Increasing penetration of post-impoundment sediments and increasing return from pre-impoundment substrate with progressively lower frequencies.
Figure reprinted from Dunbar et al. (2000) with permission
Information Needs

Information needs related to lake bathymetry and reservoir assessment can be divided into two broad categories: 1) reservoir-scale information needs, which can be satisfied by applying bathymetric technology in an integrated reservoir assessment program, and 2) technology-specific information needs that explore strengths and limitations of bathymetric technology. Crucial information is lacking, and many questions remain.

Reservoir-Scale Information Needs

What is the rate of sedimentation, and is sedimentation continuous or episodic? Repeated bathymetric surveys provide significant insight into the nature of sedimentation in a reservoir. Changes in reservoir bottom topography can be monitored over time, allowing an overall estimate of the rate of sediment accumulation and a spatially explicit representation of sediment accumulation and movement across a reservoir. Bathymetric surveys before and after major rain events can provide information on whether significant sediment movement occurred.

Technology-Specific Information Needs

To better understand data produced by bathymetric surveying, research should be conducted to explore strengths and limitations of this technology. Answering the following questions can help improve speed, accuracy, and precision of data acquisition, which is necessary for making informed decisions about reservoir management and renovation.

Topographic and acoustic sediment thickness estimation techniques

- What are the possible sources of error of this approach?
- What are the effects of sediment composition on estimating sediment thickness?
- What are the limitations to identifying the pre-impoundment bottom contour in acoustic data?
- What are the effects of scale (horizontal and vertical resolution) on accuracy?
- What spatial error results from differences between pre-impoundment published topographic data and “as-built” topographic conditions?

**Processing acoustic data for bathymetric and sediment surveying**
- What are the optimal interpolation algorithms, in terms of speed, accuracy, and precision, for bathymetry and sediment thickness estimation?
- Can advanced signal processing of acoustic echosounder data accurately identify pre-impoundment lake bottom traces?
- Can advanced signal processing of acoustic echosounder data coupled with an “acoustic library” of Kansas reservoir substrate signatures improve bottom type classification?

**Sustained Reservoir-Mapping Program**
These surveys will provide a set of baseline bathymetric elevations and sediment data. One advantage is that water quality and bathymetric data can be measured simultaneously from the same boat. Also, because surveys will be conducted with the same equipment and methods, it will be possible to compare results among reservoirs and from the same reservoir over time.

**Change Detection Studies**
These studies would involve revisiting previously mapped reservoirs, re-mapping the bathymetry and cores, and comparing past and present maps to identify sedimentation locations and rates. This element likely will not occur during the first few years of the program but eventually could grow into a major focus as baseline bathymetric and sediment data are accumulated for comparison.

**Mapping and Assessment Program**
A long-range bathymetric mapping and reservoir assessment program for Kansas will have numerous benefits. Decision makers will be able to easily assess current conditions of a given reservoir and identify and prioritize reservoirs based on sediment load and need for renovation. Enhanced knowledge of sediment deposition in reservoirs will help determine effectiveness of watershed protection practices. When dredging appears to be the best alternative to extend the life of a reservoir, sediment deposition data will indicate how much sediment needs to be removed and can help determine how much was removed by the dredger. Such a program should contain the following elements:

**Before/After Mapping, Coring, and Sediment Estimation**
Comparing high-resolution contours of bottom topography with pre-impoundment topography and selected sediment coring to verify thickness in certain locations will enable stakeholders to develop well-defined project goals and work plans. Dredging contractors can receive an accurate representation of reservoir bottom contours to be reconfigured. This will minimize unknown factors and encourage preparation of the most accurate and cost-effective bids and the most mutually acceptable work plan.
**Ad-hoc Mapping of Small Reservoirs**

In this capacity, the program can provide timely, unbiased, impartial bathymetric data and sediment estimates to help local stakeholders make management decisions relating to water quality, watershed management, and reservoir renovation.

**Large-Scale Mapping and Sediment Studies**

Because of the intensive effort required and large amount of data generated, we envision this program mapping four to six federal-size reservoirs per year.

**Reservoir Information System**

Multiple constituencies in Kansas need or desire information on water depth, sediment type, sediment accumulation, and related conditions affecting reservoirs. However, data and information are of little use unless readily and easily accessible to a wide variety of users.

**References**


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**Concept for a Long-Range Bathymetric Mapping and Reservoir Assessment Program**

- Sustained reservoir-mapping program that includes a number (≈10 to 20) of bathymetric and coring surveys per year
- Change detection studies to estimate rates and locations of sediment accumulation
- Before/after bathymetric mapping, coring, and sediment volume estimation for reservoir dredging projects
- Ad-hoc bathymetric mapping of small reservoirs for state, local, and private entities
- Large-scale federal reservoir bathymetric mapping and sediment studies
- Development of a reservoir information system