Sedimentation Resurvey Methods: Comparison of Prismoidal Method and GIS Based Method

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Abstract

Sedimentation resurveys determine the distribution of sediment, the depletion or addition of storage in the reservoir, and the trap efficiency of the reservoir. For the 2020 sediment resurvey of Rend Lake, a multi-purpose reservoir in Southern Illinois, two approaches for data collection and volumetric analysis were made. The first approach – Prismoidal Method – uses the 23 historic range lines. The second approach – Digital Terrain Model Comparison (DTMC) – uses a Geographic Information System (GIS) software, to process approximately 1,100 range lines spaced throughout the lake and sub-impoundments. The DTMC Method generally resulted in larger volumes than the Prismoidal Method, with these differences becoming less and less noticeable at increasingly higher elevations. Additionally, numerous coal mine tunnels are known to be located beneath the bottom of the lake. Previous studies hypothesized that abandoned mines were/are causing large areas to subside, resulting in an increased capacity of the reservoir. Using modern survey and data processing methods, this hypothesis is proven to be true. The comparison showed that while the Prismoidal Method produced accurate results with minimal data input, the DTMC Method uses a much larger quantity of data to produce more precise results. Smaller bathymetric details (e.g., the subsidence underneath Rend Lake) cannot be captured by the Prismoidal Method, possibly making it more difficult to look at volumetric changes holistically. Additionally, error sources for the two methods and considerations towards cost and time are discussed.

Purpose

In 2020, the US Army Corps of Engineers (USACE), St. Louis District (MVS) updated the Sedimentation Report for Rend Lake (a USACE owned multi-purpose reservoir in Southern Illinois). In previous Sedimentation Reports, 'prismoidal' volume calculations (manual geometric calculations) were performed to estimate the storage capacity of Rend Lake. These prismoidal volume calculations were based on far spaced cross sectional bathymetric data. In 2020, a new volume calculation method was also used. This method used single-beam bathymetric survey data to develop closely spaced cross sections to calculate Rend Lake's volume. This technical note compares the two methods and the results of using them on Rend Lake.

Introduction

Sedimentation resurveys, summarized in a Sedimentation Report, determine the distribution of sediment, the depletion or addition of storage in the reservoir, and the trap efficiency of the reservoir. The results of these studies may also serve as an indicator for changes that may affect authorized project purposes, operation of the project, lake facilities, and future planning at the project.

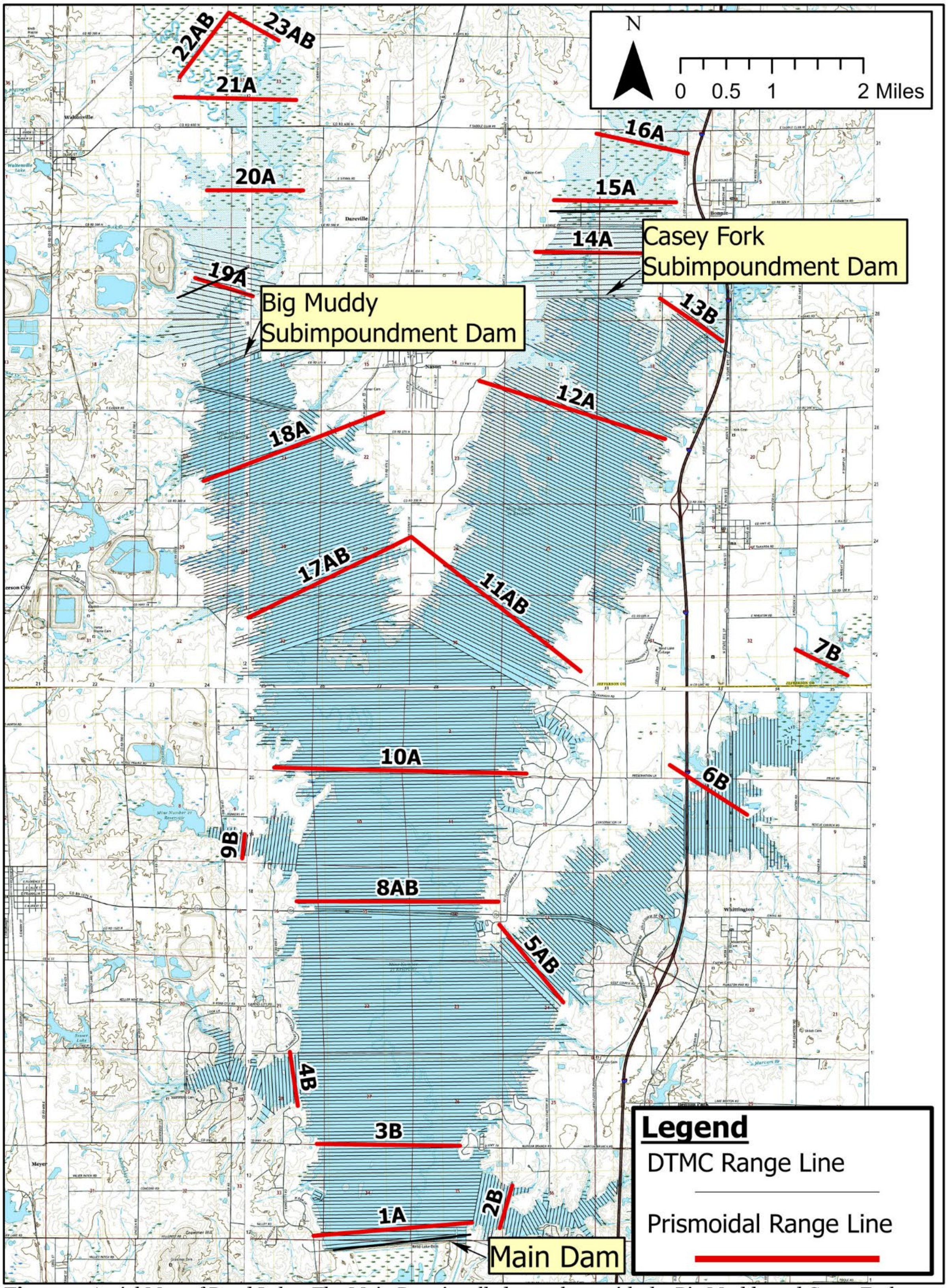

Figure 1. Aerial Map of Rend Lake. The Main Dam is called out, along with the Big Muddy and Casey Fork Subimpoundment Dams. The ranges for the Prismoidal and DTMC Methods are shown by thick red and thin black lines, respectively.

For the Rend Lake Report of Sedimentation 2020 Resurvey (2020 Sedimentation Report), finalized May 2021, two approaches for data collection and analysis were made. The first approach – Prismoidal Method – uses the 23 historic range lines (see the thick red cross section lines in (Figure 1)), which is consistent with previous resurveys. The second approach – Digital Terrain Model Comparison (DTMC) – uses a Geographic Information System (GIS) software, ESRI's ArcGIS Pro and ArcMap, to process approximately 1,100 range lines (see the density of thin black cross section lines in (Figure 1)) spaced throughout the lake and sub-impoundments.

In simple summary, the DTMC Method applies significantly more data to actually measure the lake volume, whereas the Prismoidal Method applies a small amount of data to efficiently approximate the lake volume. While the Prismoidal Method continues to provide reasonably accurate estimates based on heavily interpolated data and high levels of engineering judgement, for Rend Lake it is being superseded by the DTMC Method, which provides highly precise calculations based on lightly interpolated data and lower levels of engineering judgement.

In this report, the results of the 2020 Prismoidal Method volume calculations and the results of the 2020 DTMC Method volume calculations will be compared.

Method

Prismoidal Method

The Prismoidal Method uses 23 ranges carefully placed throughout the lake to estimate the changes in the lake geometry, depth, and volume. It implements a volume formula to simplify the shape of the lake and estimate the geometry, depth, and volume. The procedure based on the prismoidal formula for computing reservoir capacities and developed by the U.S. Soil Conservation Service (SCS) was used in previous Rend Lake sedimentation studies and also in the 2020 Sedimentation Report. The procedure was published by H.M. Eakin of the SCS as USDA Technical Bulletin No. 524, "Silting of Reservoirs," (1936), then revised by C.B. Brown in 1939. Eakin describes a range-end formula, as follows, and Figure 2 describes the variables visually.

$$V = \frac{A'}{3}\left(\frac{E_1 + E_2}{W_1 + W_2}\right) + \frac{A}{3}\left(\frac{E_1}{W_1} + \frac{E_2}{W_2}\right) + \frac{h_3E_3 + h_4E_4}{3(43{,}560)}$$

where V = capacity, acre-feet

A' = area of the quadrilateral formed by connecting the points of intersection of the ranges with a given contour, acres
Alternative to finding A' graphically, it can be determined by (as h and W are defined below)

$$A' = \frac{h_1W_1 + h_2W_2}{2(43{,}560)}$$

E = Range cross-section area, square feet

W = Width of the main stream range at a given elevation, feet

A = Total surface area of the segment bounded by the ranges, acres

h = Perpendicular distance from a range on a tributary to the junction of the tributary with the main stream; or if this junction is outside the segment, to the intersection of the thalweg of the tributary with the downstream range, feet

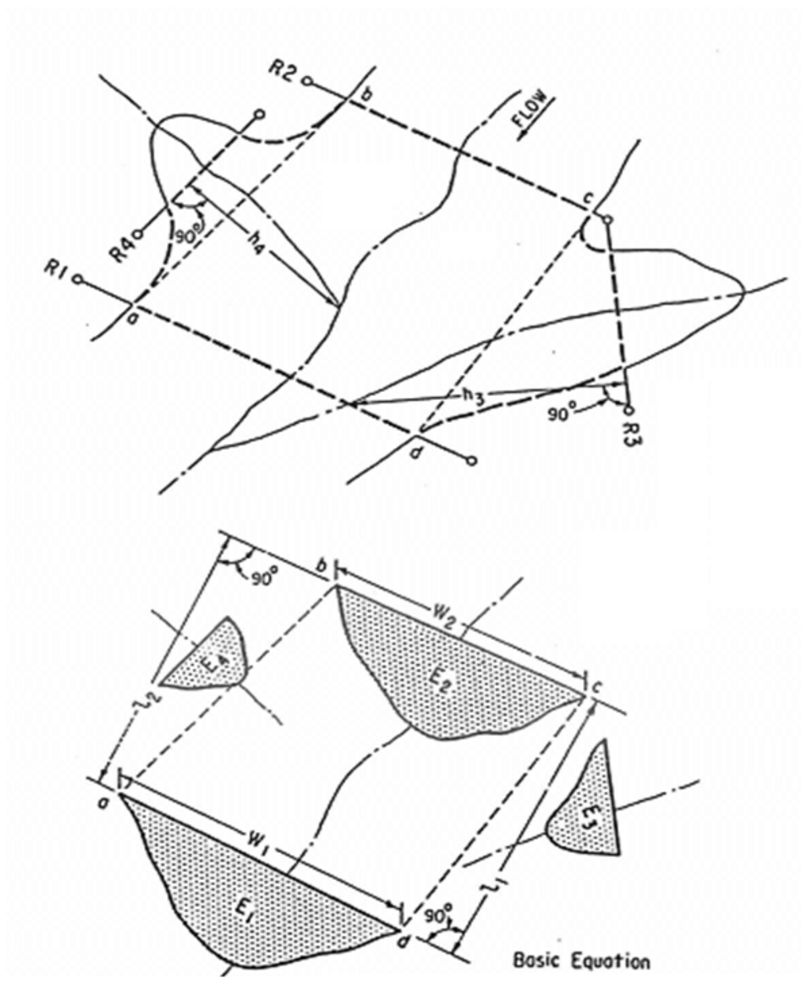

Figure 2. Terms of range-end formula for determining the capacity of a reservoir (ASCE N&R 1975)

In addition to the typical case, where there are two tributary arms (such as between Prismoidal Method range 3B and 8AB in (Figure 1), where 4B and 5AB lead to the tributary arms), the Prismoidal Method can also be used on a segment that has no tributary arms (bounded by only two ranges, such as between Prismoidal Method range 11AB and 12A in (Figure 1)) or where there is only one range (such as upstream of Prismoidal Method range 7B in (Figure 1)). Another equation is provided for calculating the volume of the reach between the most downstream range and the dam. Details of the Prismoidal Method calculation for Rend Lake can be found in Appendix E of the 2020 Sedimentation Report.

Digital Terrain Model Comparison (DTMC) Method

The DTMC Method allows millions of data points and dozens of contour lines to be imported and processed to create high-resolution digital surfaces of the topography under and around Rend Lake. Digital surfaces can be analyzed and compared in GIS software to attain surface areas, volumes, and differences in any desired region and at any desired elevation.

The survey data for the DTMC Method consisted of:

- Hydrographic single-beam cross-sections at a 300-foot interval upstream of the two sub-impoundment dams – Big Muddy Sub-Impoundment Dam and Casey Fork Sub-Impoundment Dam.

  Note that Light Detection and Ranging (LiDAR) was used in the upper portions of the sub-impoundments because bathymetric data could not be cost-effectively collected in upper portions due to limitations in technology and access.
- Hydrographic single-beam cross-sections at a 200-foot interval on the remainder of accessible areas of the lake.
- LiDAR above the lake main pool elevation

MVS used this method for the first time in 2020. An outline of the processes that MVS developed for the DTMC method is as follows. A digital terrain model of the 2020 Rend Lake survey data was built using ArcMap. The volumes and surface areas were calculated for each desired elevation on the 2020 topobathy surface. The volumes and surface areas were further divided between ranges and main lake/sub-impoundments. Further details and descriptions in the form of a step-by-step guide that outlines the ArcGIS tools used in the DTMC Method can be found in Section 13. Methods of Sediment Computations and Appendix F of the 2020 Sedimentation Report.

Error Sources

This section summarizes the main error sources for both the Prismoidal Method and DTMC Method. Some of these errors are specific to the Rend Lake study, but they could easily occur on other projects as well.

Prismoidal Method Error Sources

- Interpreting documentation related to the Prismoidal Method required a lot of engineering judgement, and few examples were found to ensure the method was being implemented correctly.
- A limited number of transects are used, which means that the lake bottom is interpolated over large spans between transects. This results in over/under predicting cross-sectional areas at the transect lines and subsequently the volumes associated with the reaches that rely on those transects.
- Final volume is derived from a simplified surface shape and area, which could result in errors to the surface area and reach geometry.
- Surveyed range data can come in shifted spatially from survey to survey, which could result in shifted range plots, changing the volume calculations.
- Individual bathymetric points do not align perfectly with each requested transect line. Therefore, in calculation of the stationing along the transect length, the length of the survey line was used instead of the length along the transect line. Since the survey line is

not perfectly straight, a distance discrepancy builds along the length of the transect. This leads to minor overall cross-sectional area error, which feeds into volumetric error via the prismoidal formula.

- Some transects might extend further than others, in both space and time. Comparison must be limited to the length of the shortest transect
- The original placement of prismoidal transects can lead to error between the Prismoidal Method and DTMC Method. In the Rend Lake resurvey, it was noted that the placement of transects around one of the lakes' largest reaches were not the best representations of the reach. To improve the volume calculation in this reach, additional prismoidal ranges that are more representative of the reach could be added. However, that would impact the congruency of long-term trends.
- Other potential sources of error include small pools that are disconnected from the rest of the main body of water and small tributaries or fingers that were often not accounted for in the prismoidal volume calculations. In these cases, the guidance was followed as with any other reach, but the equations were not intended for this scenario (and the guidance made no recommendations to better address this case). Relative to the entire lake, these areas with small pool and small tributaries or fingers are trivial, adding minimal overall error. Nonetheless, this minimal error contributes to the overall inaccuracy of the Prismoidal Method and is addressed in greater detail in the DTMC Method.

DTMC Method Error Sources

- Using LiDAR data as the surface elevation in the upper portions of the sub-impoundments and fingers could result in an underestimate of the capacity of the sub-impoundments and the lake fingers/extremities.
- Differing years and resolutions of LiDAR datasets likely result in some topographic misrepresentations of the 2020 condition. The lake bottom was interpolated between ranges (up to 200-300 feet) to calculate volumes. Results in some minor lake features being excluded/distorted, and a very small amount of error being introduced. There is a gap, along the shoreline of the lake, between bathymetry and LiDAR data. It was combined seamlessly by triangulating across the gap using GIS. The gap varies depending on the steepness of the bank in the area.

  Note: This source of error is a candidate for further study by the USACE. Further study should compare volume results from various spacing configurations to determine what magnitude of errors occur as transects are spaced further and further apart.

Deviations exist between the Prismoidal and DTMC Methods primarily due to the primary error sources, listed above. The Prismoidal Method is not considered to be inaccurate or imprecise, but the DTMC Method is very precise and very accurate due to the sheer quantity of data that is required and the objective method by which it is procured and processed. The DTMC Method in the Rend Lake study uses about 1,300,000 bathymetric data points distributed throughout the lake to compile approximately 1,100 ranges. In the DTMC method, the bathymetric data is then supplemented by LiDAR elevation data from above the lake main pool elevation of about 409.45 ft.

Cost and Time

The large quantity of data that is used for the DTMC Method allows significantly more bathymetric coverage than the Prismoidal Method, all while maintaining a comparable level of surveying manpower and cost, when existing LIDAR data is available. The result is a highly accurate assessment of lake geometry, depth, and volume. If LiDAR data is not available, project costs will increase; however, it will increase the confidence of results (LiDAR data can also be useful for other applications around the reservoir). If the reservoir being studied is undergoing dynamic changes on land (e.g., eroding banks), then the age of the LiDAR data becomes even more important.

When the DTMC Method is first performed on a reservoir, the survey lines will need laid out purposefully. Additionally, a workflow will need developed for how to manage, interpret, and present the large amount of data. This workflow will need documented, so that it can be repeated for any subsequent sediment resurveys. After using the DTMC Method once on a reservoir, it may become quicker than using the Prismoidal Method (this is the expectation for the next Rend Lake Sediment Survey, but it could vary by reservoir).

Results

This section will analyze the results of the two methods for the 2020 sedimentation resurvey at Rend Lake (the in depth comparison can be found in Appendix E of the 2020 Sedimentation Report).

The 2020 DTMC Method of volume analysis generally resulted in a larger volume than the Prismoidal Method of volume analysis, as seen in (Table 1). The percent difference shrinks rapidly as elevation increases because the proportion of total volume at higher elevations that is misrepresented by the Prismoidal Method shrinks exponentially. To further explain, a difference of 5,649 acre-feet at elevation 394.56 ft results in a computed percent difference of 13%, while a difference of 9,486 acre-feet at elevation 404.56 results in a computed percent difference of only 5%. The reason a larger quantity of difference results in a lower percentage of difference at 404.56 compared to 394.56 is because 404.56 has a total volume that is four times larger than 394.56 – and that difference in volume makes up a smaller portion of the total volume at that elevation.

Table 1. Comparison of 2020 DTMC and Prismoidal Volumes and Percent Difference

Elevation (ft. NAVD88)	2020 DTMC Volume (acre-feet)	2020 Prismoidal Volume (acre-feet)	% Difference
384.56	3,745	3,389	10%
389.56	17,261	15,544	10%
394.56	47,817	42,168	13%
399.56	100,635	92,473	8%
404.56	179,593	170,107	5%
409.56	280,752	280,426	0%

Notes:
1. A positive % difference indicates a smaller volume was calculated with the Prismoidal Method than with the DTMC Method
2. 409.56 ft NAVD88 is Rend Lake's flood-control pool elevation

Additionally, numerous coal mines and oil and gas wells have been developed in the vicinity of the project (maps of coal mines in the area were produced by the Illinois Department of Natural Resources and Illinois State Geological Survey). Many mine tunnels are known to be located beneath the bottom of the lake, as outlined in (Figure 3). Previous studies hypothesized that abandoned mines were/are causing large areas to subside, resulting in an increased capacity of the reservoir. Using modern survey and data processing methods, this hypothesis is proven to be true.

Previous studies stated that the computed increase in volume in certain reaches of the reservoir caused by ground subsidence made it impossible to accurately determine the actual amount of sediment accumulation that has occurred. While the modern DTMC Method provides more insight into this, it is still highly impractical to accurately determine the actual amount of sediment accumulation. Areas where there is no subsidence could be studied separately using DTMC data if there are concerns about specific areas. Future sedimentation studies using the DTMC Method (or similar) may be able to assess whether subsidence is still actively occurring, which could provide useful insight into the rate of sedimentation.

The DTMC Method shows that many of the major volume changes that are observed in Rend Lake are related to mine subsidence, as shown in (Figure 3). Those changes occur at the same low elevations that also report a relatively large percent difference. It makes sense that more transects (DTMC Method) provide a more accurate and more precise depiction of the subsidence, whereas fewer transects (Prismoidal Method) provide a less accurate and less precise approximation of that same subsidence. In other words, the Prismoidal Method does not fully characterize the acute areas of subsidence between its far-spaced transects, whereas the DTMC Method can better quantify the nuances of each depression with its closely spaced transects.

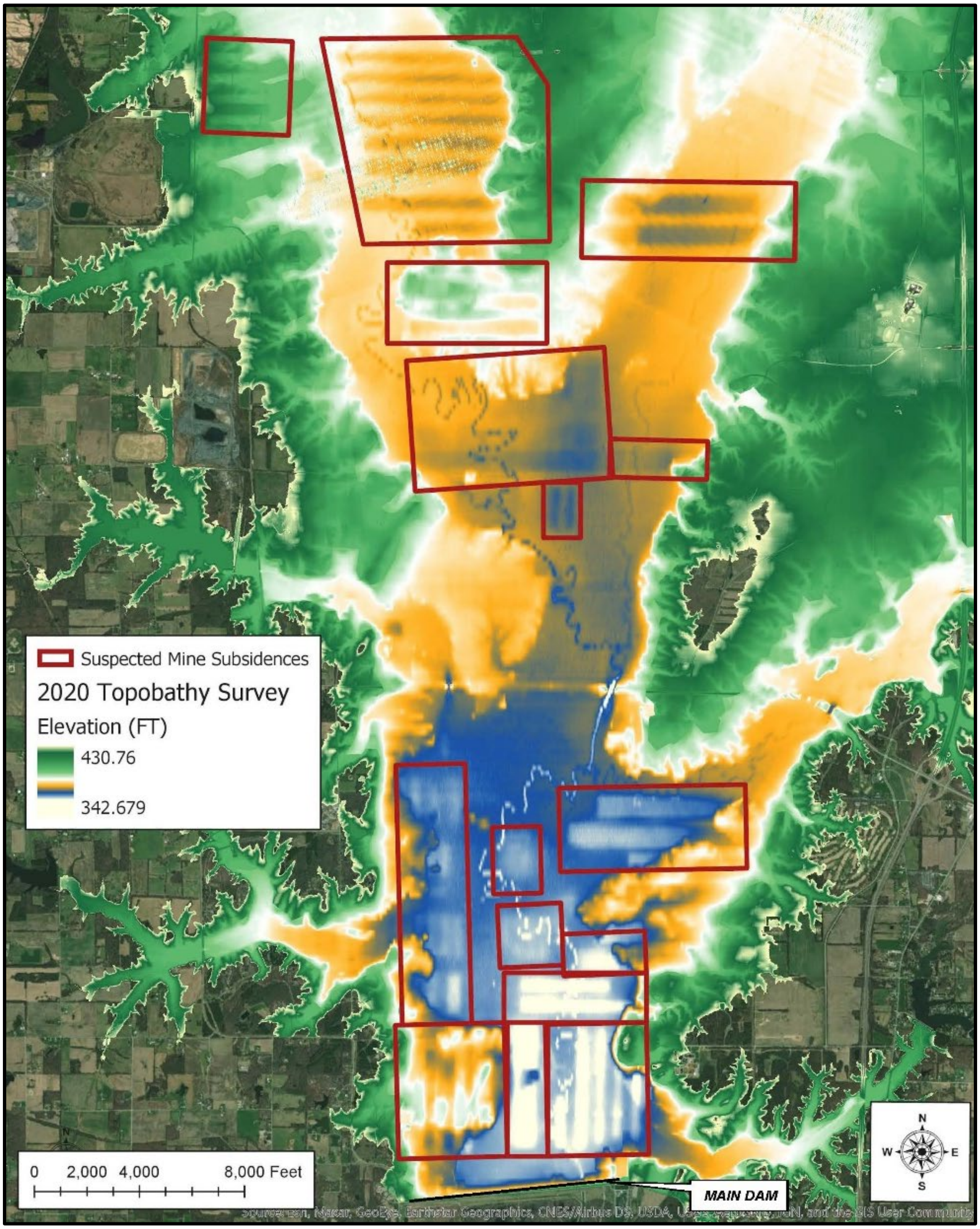

Figure 3. Aerial Image of Rend Lake Overlain with Topobathy Survey Surface. Locations of Suspected Mine Subsidence are indicated by dark red rectangles. Dramatic, rectangular shaped, changes in the topobathy surface are indicators of mine subsidence.

Conclusions

Two methods for calculating sedimentation volumes were compared in this report: Prismoidal Method (manual geometric calculations) and DTMC Method (a GIS based method). The comparison showed that while the Prismoidal Method produced accurate results with minimal data input, the DTMC Method uses a much larger quantity of data to produce more precise results. In the 2020 Sedimentation Report, the DTMC Method generally resulted in larger volumes than the Prismoidal Method, with these differences becoming less and less noticeable looking at increasingly higher elevations. Smaller bathymetric details (e.g., the subsidence underneath Rend Lake) cannot be captured by the Prismoidal Method, possibly making it more difficult to look at volumetric changes holistically. If LiDAR data is readily available for a project site, the DTMC Method can produce much more detailed results for a comparable level of surveying effort and cost. If more detailed sedimentation rate data would be useful for a reservoir, this report and the 2020 Sedimentation Report will provide guidance for considering the use of the DTMC Method.

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