A New Map of Pleistocene Proglacial Lake Tight Based on GIS Modeling and Analysis

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ABSTRACT. Glacial-age Lake Tight was first mapped by John F. Wolfe in 1942. Wolfe compiled his map from photographs of 50 USGS topographic maps, and used the 900-foot contour to delineate its shoreline. An estimate, as reported by Hansen in 1987, suggested an area of approximately 18,130 km^2 (7,000 mi^2) for the lake. Using a geographic information system (GIS) environment, an updated map of Lake Tight was developed employing the 275-meter (902-foot) elevation contour. Calculations now suggest the area of Lake Tight was 43 percent larger or approximately 26,000 km^2 (10,040 mi^2) and the volume approximately 1,120 km^3 (268 mi^3). The reconstruction of Lake Tight in a GIS creates a spatial analysis platform that can support research on the origin and development of the lake, the geologic processes that occurred as a consequence of the advance of the pre-Illinoian ice, and the origin of the Ohio River. The development of the upper Ohio Valley during the Quaternary Period remains one of the outstanding problems in North American geology. The details of the transition from the Teays River to Lake Tight, and from Lake Tight to the Ohio River, are poorly understood despite more than 100-years passing since the first significant study of those changes. A refined understanding of the area and depth of Lake Tight is essential but is complicated by fundamental unknowns—such as the location of the pre-Illinoian ice margin and the extent and consequence of isostatic flexure of the lithosphere due to ice-loading and lake-loading. Given the assumptions required for the model, the accuracy of both the raster data and the 1942 topographic maps, and the paucity of essential field data, mapping the lake shoreline at the widely cited 274.32-meter (900-foot) contour would not provide increased verifiable accuracy.

Publication Date: December 2018 https://doi.org/10.18061/ojs.v118i2.6548 OHIO J SCI 118(2):57-65

INTRODUCTION

The main goals of this study were to (1) map Lake Tight in a geographic information system (GIS) using U.S. Geological Survey (USGS) National Elevation Dataset (NED) Digital Elevation Models (DEMs), (2) determine the area and water volume of the lake, (3) compare the results with the map created by Wolfe (1942), and (4) create a GIS model that can be used as a foundation for future research. Examples of future enquiry include: investigating the damming of the Teays, the impoundment of Lake Tight and the establishment of the Ohio River, more accurately delineating the extent of the pre-Illinoian glacial front, and improving the understanding of the isostatic flexure of the lithosphere caused by the ice sheets and the impoundment of the lake.

The first geological evidence for Pleistocene Proglacial Lake Tight was documented by Hildreth (1838). In Barlow Township of Washington County, Ohio, he noted freshwater mussel fossils of the genus *Unio* in sands and gravels, plus plant remains in sand, gravel, and plastic clay—reasoning the sediments and fossils were evidence of an ancient lake. Later studies (Tight 1903; Stout and Schaaf 1931; Stout and Lamb 1938; Stout et al. 1943; Janssen and McCoy 1953; Norris and Spicer 1958) investigated geologically distinctive sediments in southern Ohio and West Virginia, which were considered lacustrine in origin. Stout and Schaaf (1931) named these sediments the Minford silts. Later studies (Webb and Collins 1967; Hoyer 1976; Bigham et al. 1991; Bonnett et al. 1991) demonstrated they were composed of more clay than silt, and Hoyer (1976) recommended the deposits be referred to as the Minford Clay Member of the Teays Formation.

The type section of the Minford Clay is located in a railroad cut of the Chesapeake and Ohio tracks (currently CSX) near Minford, Ohio (Stout and Schaaf 1931; Hoyer 1976). Lamborn et al. (1938) describe the type section as having a thickness of 7.2 meters (23.5 feet). A boring drilled by Hoyer (1976), approximately 45.7 meters (150 feet) west of the Minford Clay type section, encountered 14.5 meters (47.5 feet) of clay. Rhodehamel and Carlston (1963) measured a thickness of 31.7 meters (104 feet)

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of Minford Clay near Mt. Vernon, West Virginia, which is the thickest documented section of exposed Minford Clay. Typically, Minford Clay exposures are small in extent and often located in areas that have been altered by construction activities (Hoyer 1976).

Based on paleomagnetic studies of the Minford Clay by Bonnett et al. (1991), the age of Lake Tight has been proposed to be between 0.79 to 0.88 Ma, during the Matuyama-Brunhes reversed polarity chron. Studies of varved clays in West Virginia by Janssen and McCoy (1953) placed the minimum duration of Lake Tight at 6,500 years. Hoyer (1976) estimated the duration of Lake Tight to be between 8,000 to 10,000 years.

Lake Tight was first mapped by Wolfe (1942) using the 900-foot contour compiled from photographs of 50 USGS topographic maps. His principal evidence for an ancient lake was based on plant distributions and refugia in southern Ohio—some 96 plant species out of their normal southern and Appalachian ranges. He supported his botanical evidence with geological data, including the wide distribution of lacustrine silts and clays, former lake terraces (Tight 1903), and glacial erratics (Jillson 1927; Leverett 1929) located in Kentucky (outside of the glacial ice boundary). According to Wolfe (1942), all the erratics were found within areas of ponding or near the heads of preglacial valleys. Bailey et al. (2014) interpolated a 900-foot elevation shoreline for Lake Tight from erosional features in several locations in the former Teays River valleys of south-central Ohio. Evidence for the shoreline included stacks along ridge tops, wave cut notches, and bluffs in Mississippian sandstone. The shoreline features were identified over long distances, suggesting a continuous shoreline at the 900-foot elevation.

The current Ohio River exists because of the impoundment and subsequent draining of Lake Tight, which were the key elements in the reorganization of the Teays drainage into the Ohio drainage. Without an understanding of Lake Tight and the Teays River, a correct understanding of the Late Cenozoic evolution of the eastern part of the Mississippi River drainage cannot be attained.

METHODS AND MATERIALS

USGS National Elevation Dataset (NED) Digital Elevation Models (DEMs) provide elevation coverage for the entire US (Gesch et al. 2014). The NED is a raster elevation product from the USGS containing the most accurate elevation data available. The elevation data of the NED provides consistent datums, elevation units (in meters), and projections that allow for coordinate standardization across different analysis platforms. The Lake Tight model is developed in ArcGIS® version 10.1, software developed by Environmental Systems Research Institute Inc. (Esri®). One-arc-second DEMs were downloaded through The National Map on the USGS website (with the 3D Elevation Program providing DEM files; https://www.usgs.gov/core-science-systems/ngp/3dep). The 1-arc-second DEMs have a raster cell size of 30 meters (98 feet) for the conterminous US and a vertical accuracy of 2.44 meters (8 feet) (Gesch et al. 2014).

Eleven DEM coverages of areas of Ohio, West Virginia, and Kentucky were added to the GIS. The DEMs were combined into one DEM (Fig. 1). The GIS created a 25-meter contour (82-foot) interval feature class from the DEMs, including a 275-meter (902-foot) limiting contour for Lake Tight.

Before the GIS map could be completed, geomorphological considerations were necessary because the 275-meter (902-foot) contour elevation alone could not be used to define the lake boundary. To the northwest, the contour intersects Quaternary deposits from several glaciations. This was problematic because the Teays River is inferred to have been dammed during a pre-Illinoian glaciation (see Hoyer 1976; Bonnett et al. 1991; Goldthwait 1991), but there is little evidence of pre-Illinoian drift in Ohio (apart from some mapped in the Cincinnati area; Pavey et al. 1999).

The 275-meter (902-foot) contour follows the courses of the Muskingum River, Walhonding River, and Killbuck Creek into northern Wayne County, Ohio. In addition, the 275-meter (902-foot) contour delineates drainage networks near the Muskingum River. According to Stout et al. (1943), the Muskingum River is post-Wisconsinan. Stout et al. (1943) suggest blockage and ponding of the post-Illinoian Massillon River forced flow to the south, breaking through a divide at the county line between Muskingum and Morgan Counties, and subsequently forming the Muskingum River. Because of the inferred age for the Muskingum River by Stout et al. (1943), the Muskingum River and its tributary networks were excluded from the Lake Tight model.

To the west, in Lewis and Mason Counties, Kentucky, the 275-meter (902-foot) contour continues to the west along the course of the Licking River and its tributaries. The 275-meter (902-foot) contours do not provide a possible boundary for Lake Tight

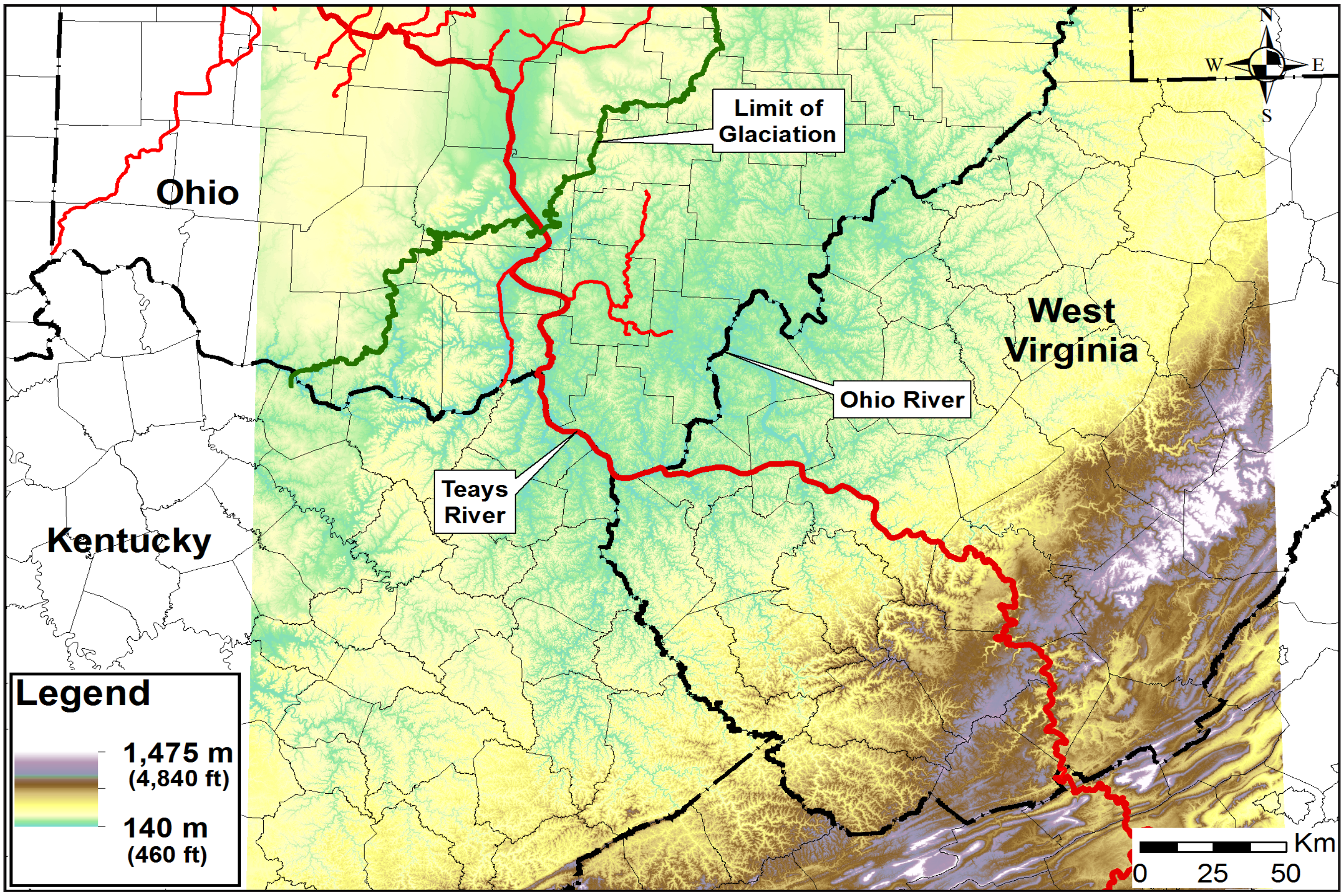

FIGURE 1. The combined DEM coverages used to create the 275-meter (902-foot) contours for the Lake Tight map. A 12th DEM was added to the southeast area for continuity. Legend shows color sequencing for land-surface elevations; bounding elevations are shown in meters (and feet). Boundaries within the states are county outlines.

until they reach the vicinity of Hamilton County, Ohio, and south and central Kentucky. Though the pre-Illinoian ice margin might have bounded the lake in Kentucky, there is little evidence of where that boundary might have been located. The present-day lack of a 275-meter (902-foot) contour in that area could be reconciled by crustal bending at the forefront of the pre-Illinoian ice margin.

It is known that isostatic flexure of the crust occurs during the advance and retreat of ice sheets, but flexure at glacial margins is only partially understood. McGinnis (1968) stated that crustal uplift (a forebulge) occurs in proximity to an ice margin because of crustal deflection beneath the ice. McGinnis (1968) used crustal tilt data in calculations to predict the amount of theoretical forebulge that occurs at the edge of an ice front. The tilt data were derived from both inferred relative vertical movements of North American glacial lake shorelines and measurements of Greenland sub-ice profiles. Crustal tilts for North American ice sheets and the Greenland ice cap, which range between 0.3% and 0.7% (Victor 1956; Farrand 1962), were utilized by McGinnis (1968) in an equation that predicts elastic crustal deformation in unfaulted crust. He calculated that a theoretical forebulge would extend approximately 262 kilometers (163 miles) beyond the ice margin. In addition, his model predicted a maximum forebulge uplift of 80 to 185 meters (262 to 607 feet) at approximately 66 kilometers (41 miles) beyond the ice front.

Fjeldskaar (1994) studied the uplift and decline of the Scandinavian glacial forebulge and argued a forebulge could be significant depending on mantle viscosity and lithosphere rigidity. The theoretical model of Fjeldskaar (1994) predicted a Scandinavian glacial forebulge uplift of 60 meters (195 feet) that occurred 15,000 years before present (BP), declining to 40 meters (130 feet) by 11,000 BP. Based on the studies of McGinnis (1968) and Fjeldskaar (1994), the pre-Illinoian ice margin could reasonably be expected to have produced a forebulge in northern Kentucky that would have constrained the western extent of Lake Tight. Despite this probability, an indefinite boundary must be assigned to the western limit of the lake that is not constrained by today's 275-meter (902-foot) contours.

To confine the northwest boundary of the lake, Quaternary deposits mapped by the Ohio Geological Survey (OGS)—and converted to a digital representation in a GIS environment (Pavey et al. 1999)—were used to define the pre-Illinoian ice margin. A geological interpretation of the Quaternary deposits was performed in the GIS to develop the estimated glacial ice margin. With no preserved deposits from the pre-Illinoian glaciation to assist with mapping the glacial limit boundary, the limit was instead generally defined at the boundary between Illinoian dissected ground moraine deposits and colluvium in unglaciated areas. For the Muskingum River area, an arbitrary boundary was created south of the divide of Stout et al. (1943). In the westernmost part of the lake, an arbitrary boundary was created to bound the lake in the area in which the 275-meter (902-foot) contour elevations are not present.

The 275-meter (902-foot) contour and the boundaries developed for the glacial ice margin, Muskingum River area, and western boundary were combined into a single linear feature class. Finally, this linear feature class was converted into a seamless polygon feature: the lake polygon. The combined DEM created previously was clipped using the lake polygon to create a new DEM with the same boundaries as those of the lake polygon (Fig. 2).

The Teays River and some of its tributaries were added to the GIS. These data were based on (1) Teays Valley segments visible on an Esri® US image of the area; (2) from the course of the Kanawha River, the New River, and part of the Ohio River; and (3) from the OGS bedrock contour GIS dataset (Ohio Division of Geological Survey 2003)—used in areas in which visual data were inadequate to estimate the course of the Teays River. The Teays River and tributaries that were based on OGS data were aligned with bedrock valleys.

Islands (or emergent ridgetops) were the final landforms to consider in the modeling of the lake. Contours that had values ≥275 meters (902 feet), within the lake bounding polygon, were initially identified as potential islands within the lake. Islands would be used as part of the calculation to determine the extent of the lake, so the definition of an island was essential to the process. Ironically, there is no consensus on what defines an island, especially a small island (see Gillespie and Clague 2009; Jennings 2014; Giaimo

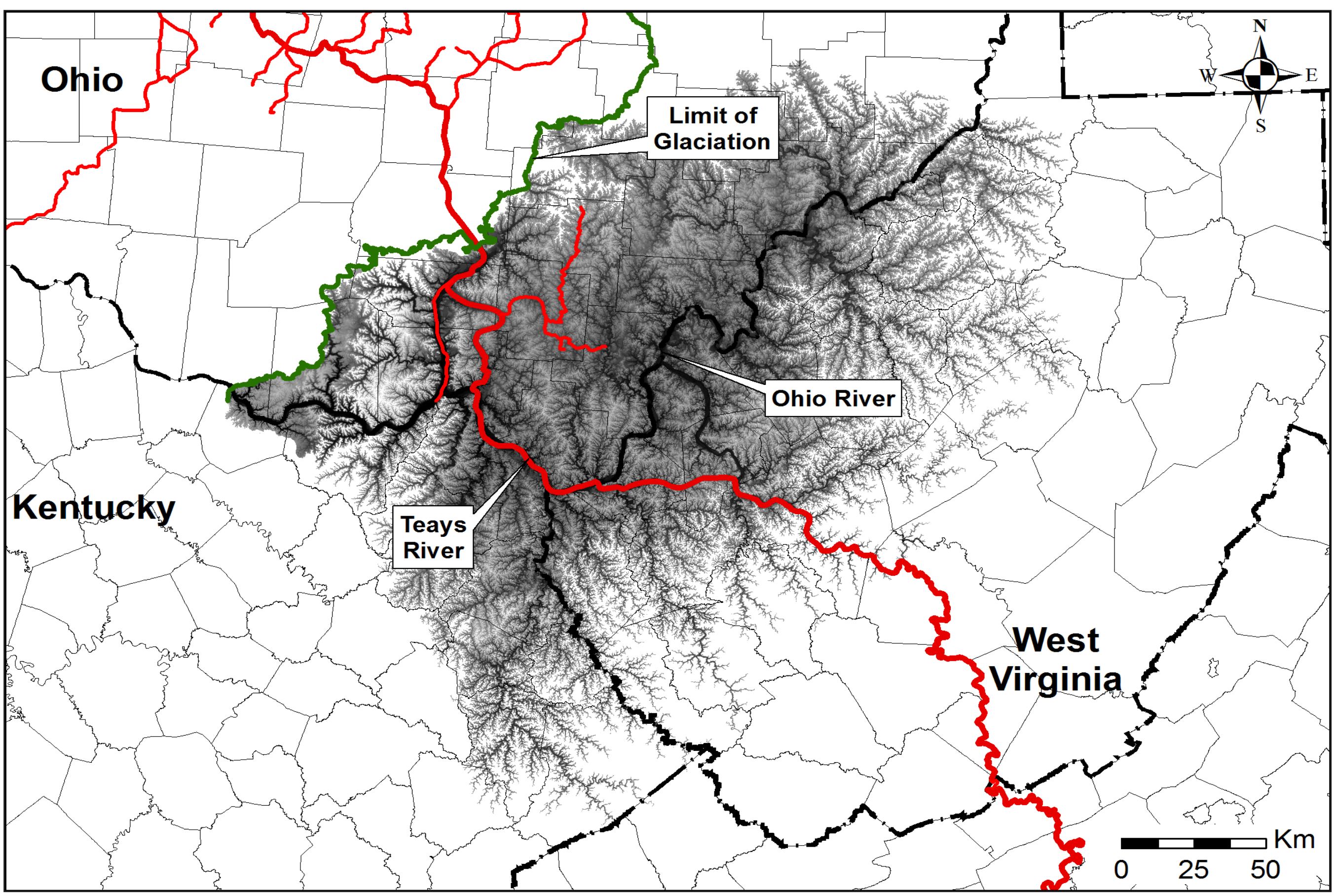

FIGURE 2. DEM corresponding to the area of the Lake Tight bounding polygon based on the 275-meter (902-foot) elevation contour. Boundaries within the states are county outlines.

2018). Bishop Rock in the Atlantic Ocean, which accommodates only a lighthouse, is claimed to be the "Smallest Island in the World," with an area of 736 m^2 (7,922 ft^2) (Jennings 2014).

Because there is no consensus on what constitutes the minimum area for a landmass to be called an island, a methodology with consistent criteria was established. A potential island would be eliminated from the dataset if there was not a large enough elevation differential, based on the vertical accuracy of the 1-arc-second DEMs of 2.44 meters (8 feet), to distinguish the potential island from the surface elevation of the water. A DEM point feature class was created from the Lake Tight polygon DEM. Island polygons that contained at least 1 DEM point that was ≥277.5 meters (275 meters + 2.5 meters; 902 feet + 8.2 feet) were considered an island.

The DEM point method is not without bias. A spatial location query of the graphical data showed some islands ≥700 m^2 (7,530 ft^2) were located between the 30-meter (98-foot) DEM points. This query captured all islands that did not have a DEM 277.5-point within them, but were of an area comparable to or greater than that of the smallest island extracted by the DEM point method. Another query, based on polygon size, identified approximately 10,500 islands that were used to create a final island feature class.

The GIS automatically calculates the areas of polygon features that are converted from linear features. The cumulative area of the island polygons was subtracted from the area of the lake polygon to determine the area of Lake Tight.

RESULTS

Like Wolfe's map of Proglacial Lake Tight (Wolfe 1942), the GIS reconstruction of the lake shows it covered an extensive area of Ohio, West Virginia, and Kentucky (Fig. 3).

The GIS estimated area of Lake Tight is 26,000 km^2 (10,040 mi^2), which is comparable to the area of current Lake Erie (Table 1). Statistical analysis shows the average bottom elevation of Lake Tight to be approximately 232 meters (761 feet) with a calculated average water depth of approximately 43 meters (141 feet). The estimated water volume of the new Lake Tight model is 1,120 km^3 (268 mi^3), or approximately 2.3 times greater than that of current Lake Erie and approximately two-thirds the volume of current Lake Ontario (Table 1).

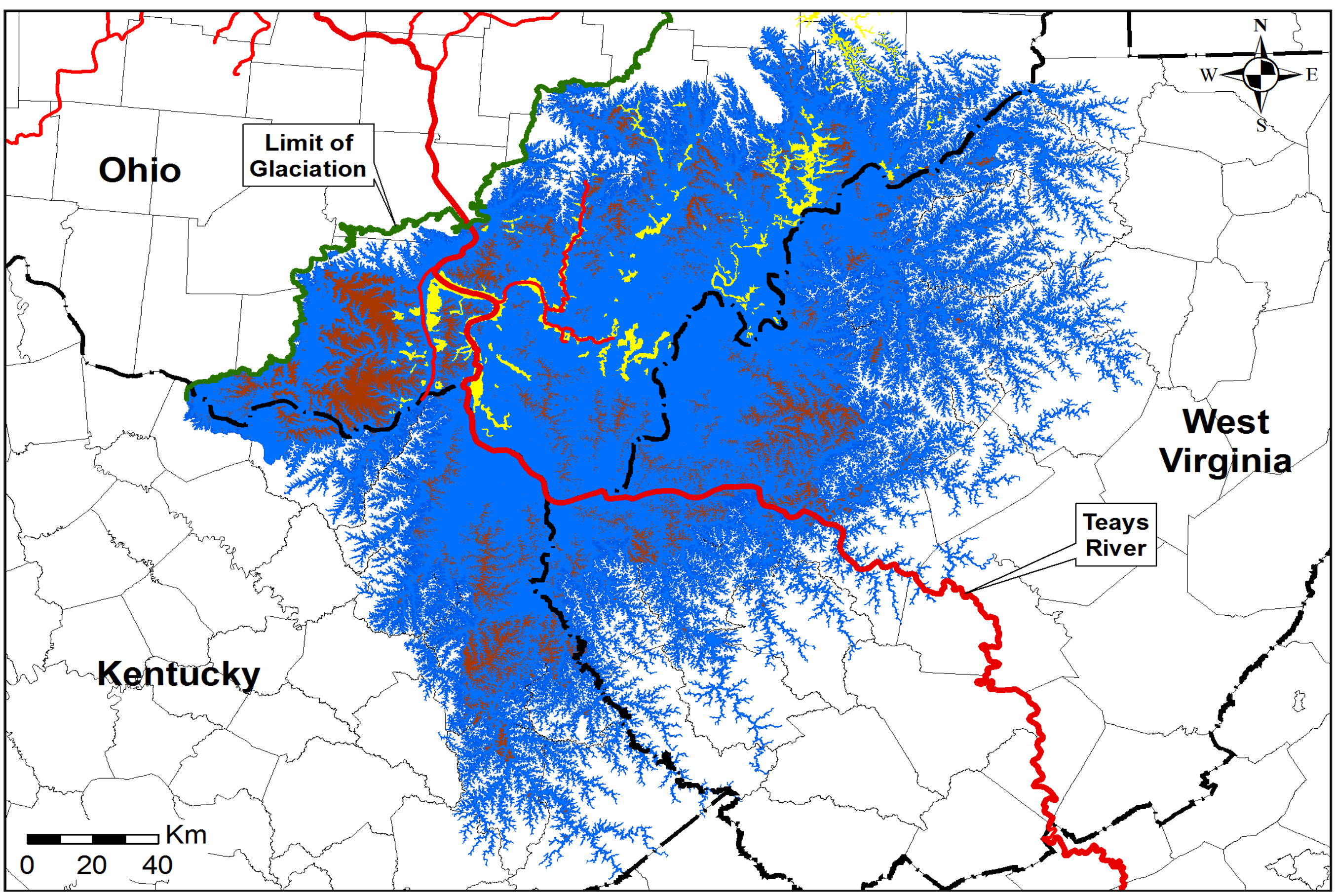

FIGURE 3. GIS model of Proglacial Lake Tight in blue. Islands in dark brown. Mapped exposures of lacustrine sediments (mostly Minford Clay) are in yellow (from Pavey et al. 1999). Boundaries within the states are county outlines.

Table 1
Area and volume comparisons of the Wolfe (1942) map, GIS Lake Tight map, Lake Erie[a], and Lake Ontario[a]

Model/existing lake	Area		Volume	
	km²	mi²	km³	mi³
Wolfe (1942) map	18,130 [b]	7,000 [b]	n/a [c]	n/a [c]
GIS Lake Tight	26,000	10,040	1,120	268
Lake Erie	25,700	9,910	484 [d]	116 [d]
Lake Ontario	18,960	7,340	1,640 [d]	393 [d]

[a] Lake Erie and Lake Ontario data from Canada and United States (1995).
[b] Area for Wolfe's map was reported by Hansen (1987).
[c] No volume was estimated for the Wolfe (1942) map.
[d] Measured at Low Water Datum (Canada and United States 1995).

Unlike Lake Erie, which has approximately 36 islands (Gora 2018), the new Lake Tight model contains over 10,000 islands (or emergent ridgetops). Though most of the islands are small—the smallest is approximately 700 m^2 (7,530 ft^2)—283 of them each has an area greater than 1 km^2 (0.38 mi^2); the sum of those 283 islands encompasses approximately 2,425 km^2 (936 mi^2). The largest island modeled in Lake Tight has an area of 348 km^2 (134 mi^2).

DISCUSSION

Despite the processing power of a GIS, the GIS model of Lake Tight is only an estimate of the lake's extent, geometry, and water volume. Uncertainties arise because of the paucity of field data for the lake area, the uncertainty of the location of the pre-Illinoian ice margin, a lack of understanding of the amount of isostatic flexure of the lithosphere in this area of North America, and a lack of substantive data on drainage divides.

Overall, the fundamental approach of the GIS methodologies used to map Lake Tight is comparable to that of Wolfe (1942). Whereas Wolfe (1942) used the 900-foot contour to determine the extent of the lake, this study used the 275-meter (902-foot) contour. Wolfe created his map manually from 50 USGS topographic maps, which were photographed for compilation. All data used to develop the GIS model were added into the GIS for modification, evaluation, processing, query, and measurement. Because of the assumptions required for the model, the accuracy of both the raster data and the 1942 topographic maps, and the paucity of essential field data, mapping the lake shoreline at the widely cited 274.32-meter (900-foot) contour would not provide increased verifiable accuracy.

The coverage area of the map by Wolfe (1942) is not as extensive as the comprehensive coverage achieved in the GIS (Fig. 4). The GIS Lake Tight extent—an area of 26,000 km^2 (10,040 mi^2)—is approximately 43% greater than the area of 18,130 km^2 (7,000 mi^2) for Lake Tight as reported by Hansen (1987). Wolfe (1942) did not mention the area of Lake Tight. The area of 18,130 km^2 (7,000 mi^2) may be derived from an estimate of the distribution of silt deposits in over 14 counties in south-central Ohio by Stout and Schaaf (1931).

Anomalies

Some exposures of lacustrine sediments (Pavey et al. 1999), mostly attributed to the Minford Clay, are outside of the 275-meter (902-foot) contour boundary of the GIS lake model. Most of these deposits are located in Guernsey, Muskingum, and Noble Counties, Ohio (Fig. 4). Though these sediments suggest Lake Tight was larger than mapped in the GIS, that cannot be reconciled easily with the GIS Lake Tight model. This is because the origin of the Muskingum River is tied to the Wisconsinan glaciation (Stout et al. 1943) and there is a lack of literature addressing the degree of isotatic flexure during the advance of the pre-Illinoian ice and the impoundment of the lake. However, it can be speculated that these lacustrine sediments could be attributed to Lake Tight because of their proximity to the lake. If these sediments are from Lake Tight, it suggests influence of isostatic depression of the lithosphere by the ice; thus, today's 275-meter (902-

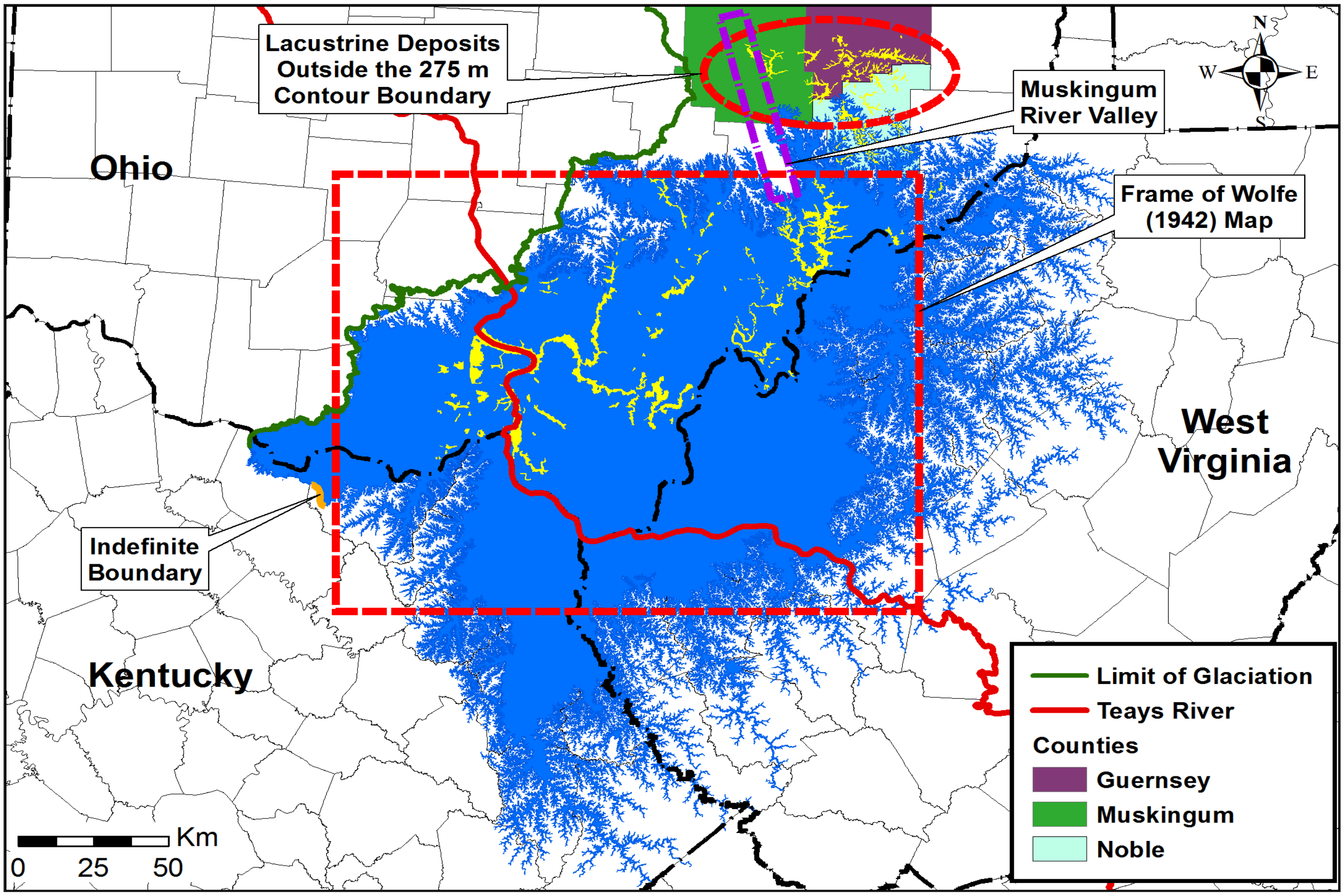

FIGURE 4. GIS Lake Tight model (in blue) with an overlay of the area mapped by Wolfe (1942). Dashed ellipse highlights exposures of lacustrine sediments (in yellow) north of the lake (lacustrine sediment locations from Pavey et al. 1999). The Muskingum River Valley is denoted by a purple rectangle. The western indefinite boundary is identified by an orange line. Islands have been removed for clarity. Lines within the states are county outlines.

foot) contour was at a lower elevation during the time of Lake Tight. If this is correct, then the shoreline could have been an estimated 40 kilometers (25 miles) north of where it has been mapped in the GIS, and the lake area would be greater than what was modeled.

Because of Lake Tight's role in transforming the Teays drainage into the current Ohio River drainage, some drainage divides that exist today certainly did not exist then; conversely, some drainage divides that existed during the time of Lake Tight do not exist now. The GIS model does not incorporate these factors in its analysis.

The precise location of the ice dam that dammed the Teays River is not known. It is inferred to be in the vicinity of Chillicothe, Ohio (see Hoyer 1976; Bonnett et al. 1991). Because of the complete removal of earlier glacial deposits through erosion and subsequent glacial advances, or burial by younger deposits, the limit of glaciation during the time of the impoundment of Lake Tight cannot be accurately delineated. The GIS glacial margin is just one of several interpretations in the literature (see White 1951; Wayne 1952; Goldthwait et al. 1961; Bonnet et al. 1991; Granger et al. 2001).

To approximate the change that might occur in the area of the lake by using a different glacial ice margin, the margin was parallel-copied 2 kilometers (1.24 miles) northwest of its location in the GIS model. The original GIS Lake Tight polygon was modified to abut the copied linear ice margin feature and the 275-meter (902-foot) contours in the extended area. The movement of the ice margin from its original location to the new location increased the area of the lake by 273 km^2 (105 mi^2), which is approximately 1% greater than the extent of the original Lake Tight model. As expected, a different ice margin changes the lake area, but based on the results, it suggests the effect would be minor. The methodology ensured the lake extent would increase, but that would not be expected if another published ice margin is used such as those by White (1951); Wayne (1952); Goldthwait et al. (1961); Bonnet et al. (1991); and Granger et al. (2001). The ice margin provides a definitive boundary for the lake, but the contour locations and geometries are integral as well.

An advantage of a glacial lake reconstruction using a GIS is its applicability to modeling earth features and processes; for example, Teller and Yang (2015) used GIS and DEM data to map Glacial Lake Agassiz shorelines, and Yang and Teller (2005) used GIS to model the history of the Lake of the Woods. Still, there are limitations that must be considered with a GIS. In the Lake Tight model, the GIS strictly adhered to the 275-meter (902-foot) contour, providing an accuracy that may have "over-modeled" the lake boundary. A more predictive boundary, based on an estimation of the topography during the time of Lake Tight, cannot be achieved in the GIS because of the general sparseness of geologic field data. There is no straightforward approach to reconstruct an approximate, or even inferred, topography of the mid-Pleistocene using the GIS alone, especially over the broad area that Lake Tight encompassed.

CONCLUSION

Much still needs to be understood about the damming of the Teays River, the impoundment of Lake Tight, and Lake Tight's subsequent draining. A GIS was utilized to model Lake Tight using spatial and elevation data, following the general methodology of Wolfe (1942). Though the Lake Tight GIS model is only an estimate of the extent and volume of the lake, there are some advantages of the GIS and its model: (1) the model can be readily and easily modified to incorporate new data; (2) the model provides a data repository for future research, including (but not limited to) Lake Tight, the Teays River system, isostatic flexure of the lithosphere, the pre-Illinoian glaciation, the transition between Lake Tight and the Ohio River, and the identification and interpretation of geologic features that could better constrain the extent of the lake; (3) the GIS can perform complex spatial analysis; (4) the GIS can manipulate and analyze vector and raster data in 2D and 3D space; and (5) the GIS can incorporate and process data from many digital sources as well as output data in a variety of digital and hardcopy formats.

In summary, the GIS model estimate of the area of Lake Tight is 26,000 km^2 (10,040 mi^2) and the estimate of the water volume is 1,120 km^3 (268 mi^3). The original map by Wolfe (1942) could not be used to determine an approximate water volume of the lake; today's technologies, such as the use of raster data in a GIS, can provide such an estimate. The previously published extent of 18,130 km^2 (7,000 mi^2) by Hansen (1987) may not be the area of Wolfe's Lake Tight map; the area estimate may have come from the areal silt deposit estimate of Stout and Schaaf (1931). The comparison of the estimated area of the GIS Lake Tight map with that of Wolfe (1942) has turned out to be a minor element of this study. More importantly, the Lake Tight dataset is capable of supporting research on the Quaternary history of the US east of the Mississippi River. Such research topics could include: the pre-Illinoian glaciation, the Teays River and its subsequent damming, the evolution of Lake Tight and its role in the transition from the Teays drainage to the Ohio River drainage, and the geological and biological changes that have occurred because of those events.

ACKNOWLEDGEMENTS

I would like to thank Kurt Shoemaker, Professor of Geology at Shawnee State University, for the guidance and encouragement he gave me to present an earlier version of the GIS Lake Tight Model in a poster session at the GSA Southeastern Section Meeting in 2014. I am indebted to him for his patience, advice, and critiques in the development of this more comprehensive manuscript.

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