

Geologic Framework of Two Contrasting Nearshore Areas of Michigan, and New Hypotheses for Relationships Among Geology, Ground-water Flow, Water Quality, and Ecology

Lundstrom, S.C., S.K. Haack, B.P. Neff, H.W. Reeves, L.R. Rukstales, K.C. McKinney, D.O. Rosenberry, J.F. Savino, D.R. Passino-Reader, and N.G. Grannemann, U.S. Geological Survey; E-Mail: Scott Lundstrom at sclundst@usgs.gov

Introduction. Development of 3-D geologic models for the Great Lakes is necessary to improve understanding of ground-water flow regimes and their effects on nearshore water quality and ecology (Haack et al, unpub. data). Improved understanding of the hydrogeologic framework is needed to address the significance of ground water to the Great Lakes (Grannemann et al, 2000) and their water balance (Neff and Killian, 2003). Such research needs to include development and testing of geologic models (Sharpe et al, 2002) that help predict variability of hydrogeologic properties within and linkage between Quaternary sediments and bedrock. Here we discuss the hydrogeologic settings and salient information gaps for two contrasting areas of Michigan, and we offer new hypotheses about geologic controls on the ground-water flow system, water quality, and ecology of the nearshore environment of the Great Lakes. The two areas are Monroe County along Lake Erie in southeastern Michigan, and the Grand Traverse Bay region along Lake Michigan in the northwestern Lower Peninsula (Figure 1). The Quaternary geology and geomorphology of the two areas differ markedly. Monroe County is characterized by low relief and has relatively thin sediments of low permeability (Mozola, 1970; Reeves et al, 2004). In contrast, the Grand Traverse Bay region has relatively high relief glacial geomorphology (Lundstrom et al, 2003) formed by thick glacial sediments of generally high permeability.

Methods. The data and methods that we used were not uniform within the two study areas, nor between them. The data and methods used reflect the varying availability of data, the natural settings, societal infrastructure, and project objectives for the two areas. Water-well data (drillers logs from the Michigan Department of Environmental Quality, 2003) were available for both areas, though the concentration and quality of data are spatially variable. The depth and altitude for the top of bedrock is better constrained in Monroe County because most water wells there penetrate relatively thin Quaternary sediments of low permeability to obtain water supplies from bedrock. In contrast, most wells in the Grand Traverse region obtain water within Quaternary aquifers and do not reach bedrock. For this area, we used available oil and gas well logs to constrain Quaternary sediment thickness and bedrock geology. Monroe County coastal sites comprise the pilot study area of the USGS Great Lakes nearshore integrated science group. In the first year of this pilot study, we obtained preliminary results on nearshore hydrology (particularly hydraulic potential), water quality, biology, and geologic setting of two sites along Lake Erie to investigate the effects of quarry dewatering (Haack et al, unpub. data). Results from the Grand Traverse Bay region mainly reflect new surficial geologic mapping during the past year (Lundstrom et al, 2003), as part of the Central Great Lakes Geologic Mapping Coalition effort (Berg et al, 2000). As part of this work, exposures (mostly at gravel pits) were examined during field reconnaissance of the landscape to help characterize map units. Contacts and drumlin long axes were located using GSMCAD (Williams, 2003) on 65 1:24,000 7.5-minute topographic quadrangles that cover the area, supplemented by use of a PG-2 plotter for analysis of aerial photographs. We combined available DEM data (10 meter data for most of the nearshore area and 30 meter data for some of the inland area) with bathymetric data for Lake Michigan (Holcombe et al, 1996).

Monroe County. The geologic framework of the county mostly consists of clay-rich Quaternary sediments that overlie the subcropping bedrock aquifer comprised of a gently northwest-dipping Silurian and Devonian sequence of predominantly carbonate rocks (Figures 1 and 2). Northeast-trending bands of subcropping bedrock that decrease in age northwestward are the result of preglacial and subglacial

Figure 1.

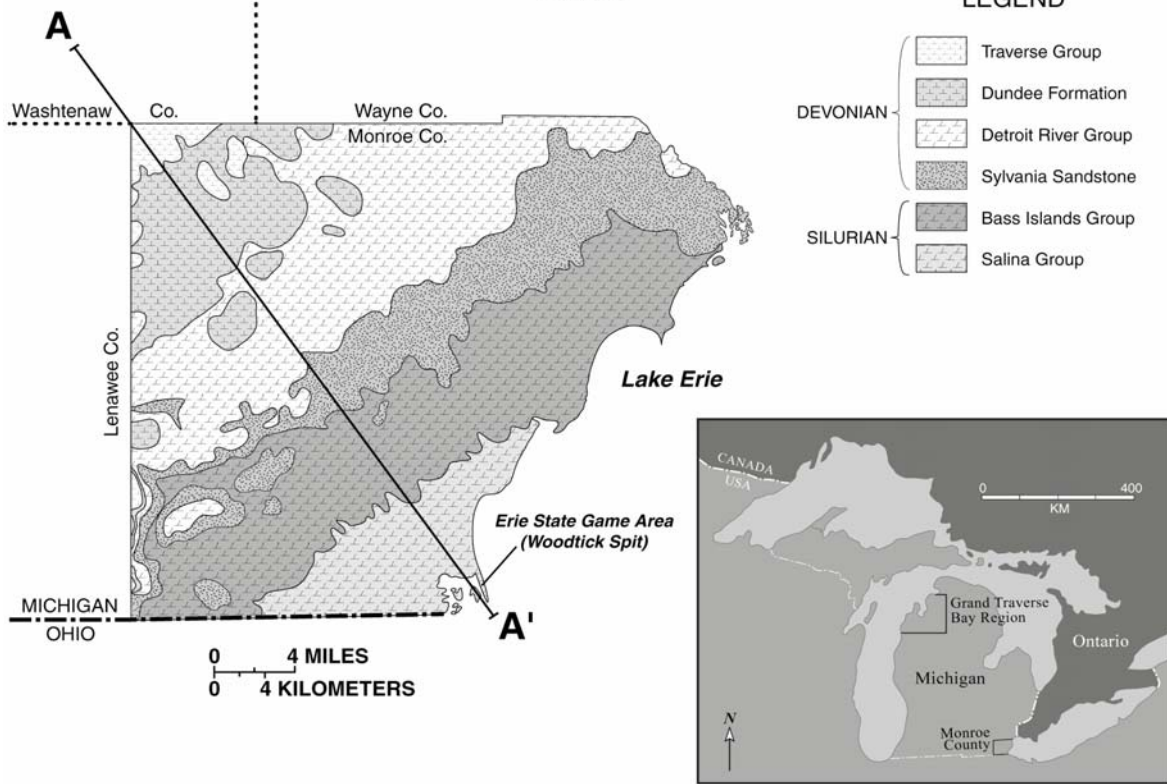


Figure 2a.

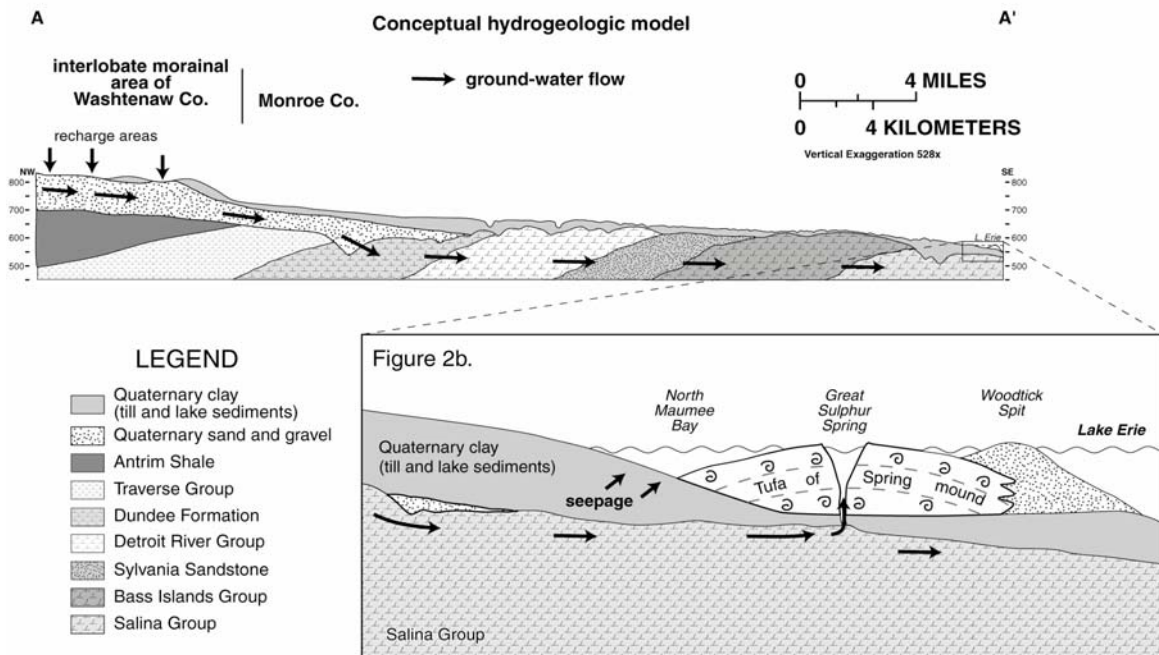


Figure 1. Bedrock geologic map of Monroe County (Quaternary sediment cover not shown).

Figure 2a. Hydrogeologic cross section showing hypothesized ground-water flow.

**Figure 2b. Inset of geomorphic and hypothesized stratigraphic relations of the nearshore zone of
Erie State Game Area.**

erosion superimposed on strata that dip gently northwest toward the center of the Michigan Basin (Dorr and Eschman, 1970). The subcropping stratigraphic sequence includes the Silurian Salina and Bass Islands Groups, and the Devonian Detroit River Group, Dundee Limestone, and Traverse Group. In this area, these strata are predominantly carbonates and dolomites, interbedded with less extensive evaporitic shales and sandstone. Northwestward, toward the depocenter of the Michigan Basin, some of the dolomitic strata of the Salina and Detroit River Groups grade to thick evaporite deposits (Landes, 1945). The carbonates and evaporitic rock types are subject to dissolution by groundwater. In similar settings elsewhere along the margin of the Michigan Basin, as in Macomb and St. Clair Counties and in the Mackinac Straits region, stratigraphic and structural relations indicate dissolution of the Salina Group. The overlying Traverse Group and Dundee Limestone also have formed karst features in northeast Michigan (Dorr and Eschman, 1970). In western Monroe County, sinkhole morphology is probable evidence of active dissolution of Silurian and Devonian carbonate aquifers in postglacial time. North and west of Monroe County, these carbonate strata are overlain by relatively impermeable shales of Devonian and Mississippian age, including the Antrim, Bedford, and Coldwater Shales. (Figures 1 and 2) Just west of the coastal Erie State Game Area (ESGA), water-well records indicate an aligned set of closed depressions in the bedrock topography that is not reflected in the surface topography. The bedrock topography buried by Quaternary sediments may indicate a collapsed karstic passage that transmits ground water toward the Erie State Game Area.

Quaternary sediments of Monroe County form a low-relief plain. Hydrogeologic investigations (Mozola, 1970; Nicholas et al, 1996; Reeves et al, 2004) and water-well records (Michigan Department of Environmental Quality, 2003) indicate that most of the Quaternary deposits are fine-grained, clay-rich material that include glacial till and glaciolacustrine sediment. These low-permeability sediments act as confining beds to ground-water flow between the underlying bedrock aquifers and the surface. For most of the county, Quaternary sediment thickness ranges from about 3-17 m. However, in the northwest corner of the county, a thickness of up to 50 m is transitional to a greater thickness of Quaternary sediment in adjoining parts of Lenawee and Washtenaw Counties. These relatively thick sediments are associated with an interlobate moraine belt that includes the Defiance and Fort Wayne moraines (Dorr and Eschman, 1970). Though clay-rich till also covers the surface of portions of these moraines, glaciofluvial sand and gravel underlie the clay-rich surfaces of the moraines. The sand and gravel may form permeable surficial recharge areas northwest of Monroe County. However, the extent of these recharge areas is unknown (Reeves et al, 2004). (Regionally, the bedrock aquifer is thought to be recharged predominantly in south-central Ohio and Indiana. From the recharge area, ground water moves northward until it meets saline water in the Michigan Basin and then discharges either to surface-water in Indiana and northern Ohio or to Lake Erie (Bugliosi, 1999)). The sand-and-gravel units continue under surficial clay units and are contiguous with confined aquifers in northwestern Monroe County. Additional hydrogeologically-isolated belts of sand-rich surficial sediments occur in portions of Monroe County; these sediments are mainly beach and nearshore deposits of prehistoric high-lake levels during late glacial and postglacial time. At the Erie State Game Area, a prominent coastal spit, the Woodtick Peninsula (Spit), formed during the late Holocene. The spit forms a barrier that protects a coastal marsh area on its west side. In the center of the marsh, emergent land surrounds a major natural spring, the Great Sulphur Spring (Figure 2b). The rim of the pond and the emergent land around the spring is a tufa composed of calcareous cemented floral and faunal remains that presently thrive in the spring-pond. The water chemistry of the spring indicates that it discharges from the subcropping Silurian bedrock aquifer of the Salina Group (Haack et al, unpub. data). The Salina carbonates are part of an aquifer that is contiguous in an upflow direction (Nicholas et al, 1996) with similar, overlying Silurian/Devonian strata.

Grand Traverse Bay region. In contrast to Monroe County, the six-county region around Grand Traverse Bay (GTB) of northern Lake Michigan is characterized by greater topographic relief and greater permeability, thickness, and complexity of the Quaternary sediments, which include common glaciofluvial and deltaic sand and gravel instead of the clay-rich sediments of Monroe County. Within 10 to 40 km of the GTB coastline, the landscape is characterized by an anastomosed network of large subglacial (tunnel) valleys (Figure 3) which are incised into drumlinized uplands composed of loamy till

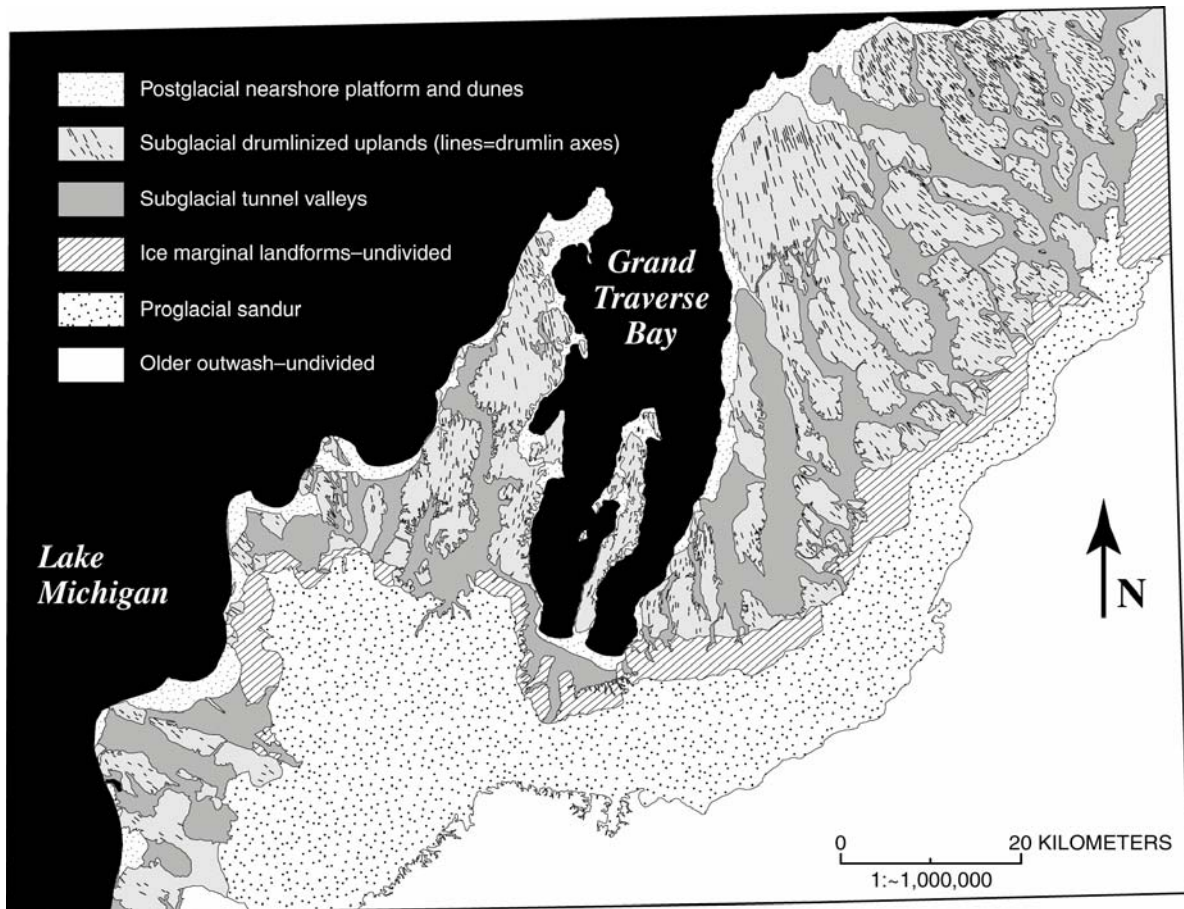


Figure 3. Glacial geomorphic map of the Grand Traverse Bay region (simplified from Lundstrom et al, 2003).

over bedded sand and gravel. Locally, the tunnel valleys are partially occupied by deep inland lakes and extensive wetlands that include groundwater discharge areas. The tunnel valleys also occur offshore to form prominent bathymetric features of northern Lake Michigan, including the arms of Grand Traverse Bay. The bedrock of this area is somewhat similar to that of southeastern Michigan, including a sequence of Devonian limestone, the Traverse Group, which is locally exposed in the coastal regions of Charlevoix and Antrim Counties. The limestones dip southeastward away from the coast and toward the Michigan Basin depocenter. The Traverse Group is overlain by younger impermeable shales (Antrim, Ellsworth, Sunbury, Coldwater), where they occur southeastward of their erosional limit beneath Quaternary sediments. Southeastward from the coast, surface elevations rise to more than 250 m above Lake Michigan and Quaternary sediment thickness increases to greater than 200 m. In these high areas, extensive

glaciofluvial sand-and-gravel aquifers (sandur, outwash, Figure 3) are at the surface just beyond the southern limit of the tunnel valleys and other subglacial terrain. Similar to their prominent expression in surface topography, tunnel valleys are also incised into bedrock, especially where the bedrock surface occurs beneath relatively thin Quaternary deposits near the coast. Bathymetry of Grand Traverse Bay and of deep linear lakes necessitates that tunnel valleys have been locally eroded below the base of the impermeable bedrock shales and into the underlying carbonate aquifers of the Traverse Group. However, the thickness and stratigraphy of Quaternary sediments under these water bodies is largely unknown. Landward, the nature of bedrock topography beneath tunnel valleys is less well constrained than near the coast, but a transect of drillholes in southern Charlevoix County provides evidence for coincident bedrock valleys and surficial tunnel valleys. The lithology and hydrogeologic properties of Quaternary sediments of the tunnel valleys is not characterized at depth, but surficial exposures indicate a wide variety of sediments: glacial sand and gravel of high permeability, melt-out till of low permeability, and postglacial alluvium, organic deposits, marl and other lacustrine sediments. Tunnel valleys include extensive areas of ground-water discharge to wetlands, lakes, rivers, and coastal embayments, as well as permeable Quaternary sediments that affect ground-water flow from upland recharge areas toward Lake Michigan. Geologic drilling and geophysical investigations are needed to characterize these features. Because the geologic expression of tunnel valleys was not considered by Boutt et al (2001), their modeled groundwater flux for the Grand Traverse Bay region could have been significantly underestimated. The Finger Lakes of central New York State are somewhat similar to the tunnel valleys of the GTB region. Seismic reflection studies (Mullins and Eyles, 1996) have shown thick Quaternary sediment fills beneath the elongate Finger Lakes, and the basal sediment typically includes permeable sand and gravel that form aquifers.

Hypotheses. In Monroe County, biogenic tufa formation by nearshore ecosystems dependent on large, sustained regional ground-water discharge from a karstic bedrock aquifer has resulted in deposition of a large spring mound at Erie State Game Area (Figure 2b). Groundwater discharge and tufa mound formation are linked to rising lake levels of Lake Erie during late Holocene time. The east flank of the spring mound forms a shoal against which longshore drift and sedimentation has formed the spit of the Woodtick Peninsula. The spit probably has accreted vertically and perhaps laterally during spring mound growth and rising lake level. The spring area may be localized where a buried karstic bedrock valley intersects and/or has developed within a more permeable or thin window through the Quaternary sediments and into the nearshore zone of western Lake Erie.

Because recharge of groundwater into bedrock aquifers through the confining beds of Quaternary sediments in Monroe County is very limited, sufficient recharge to balance discharge in the nearshore region would probably require recharge outside of Monroe County as suggested by Bugliosi (1999) and as shown in Figure 2a. The chemistry of the discharging spring water also indicates a remote water source. For the moraine belts to supply recharge, lateral flow of ground water southeastward above the confining beds of Devonian and Mississippian shales and below confining beds of Quaternary tills is required to recharge Silurian and Devonian carbonate bedrock aquifers beyond the subcropping erosional limit of the bedrock shales.

Ground-water discharge in nearshore environments of the Grand Traverse Bay region is also significant to water quality and aquatic ecology, but the effects are different than those in Monroe County and are largely affected by the different glacial geology of this region. Here, the calcium bicarbonate dominated water chemistry is probably controlled by the abundance of regionally derived Paleozoic limestone clasts in the glaciofluvial aquifers. The chemistry of discharging ground water favors biogenic carbonate precipitation, which commonly occurs in

rivers, wetlands, and nearshore settings, thus forming additional varied and unique substrates and integral ecosystem components. Most streams are groundwater-fed and provide habitat for cold-water fish assemblages, including trout species. There are several factors that make it likely that the magnitude of ground-water recharge in northern Michigan and resulting ground-water flux toward the nearshore setting of the Grand Traverse region should be significantly greater than in southeast Michigan. These factors include cooler climate, greater lake-effect snowfall, greater effective moisture, larger hydraulic gradients, and more permeable sediments favoring greater infiltration and flow.

References

- Berg, R.C., N.K. Bleuer, B.E. Jones, K.A. Kincare, R.R. Pavey, and B.D. Stone. 2000. Mapping the glacial geology of the central Great Lakes region in three dimensions-a model for State-Federal cooperation: U.S. Geological Survey Open-File Report 99-349.
- Boutt, D.F., D.W. Hyndman, B.C. Pijanowski, and D.T. Long. 2001. Identifying potential land use-derived solute sources to stream baseflow using ground-water models and GIS: *Ground Water*, v. 39, p. 24-34.
- Bugliosi, E.F. 1999. The midwestern basins and arches regional aquifer system in parts of Indiana, Ohio, Michigan, and Illinois - Summary: U.S. Geological Survey Professional Paper 1423-A, 46 p.
- Dorr, J.A., Jr. and D.F. Eschman. 1970. *Geology of Michigan*: Ann Arbor, Michigan, University of Michigan Press.
- Grannemann, N.G., R.J. Hunt, J.R. Nicholas, T.E. Reilly, and T.C. Winter. 2000. The importance of ground water in the Great Lakes Region: U. S. Geological Survey Water Resources Investigations Report 00-4008.
- Haack, S.K., B.P. Neff, D.O. Rosenberry, J.F. Savino, and S.C. Lundstrom, S.C. A preliminary survey of the effect of groundwater exchange on nearshore habitats and water quality of Western Lake Erie: *Journal of Great Lakes Research*.
- Holcombe, T.L., D.F. Reid, W.T. Virden, T.C. Niemeyer, R. De laSierra, and D.L. Divins. 1996. *Lake Michigan Bathymetric Poster and Digital Data on CD-ROM*, U.S. Department of Commerce, National Oceanic & Atmospheric Administration Report MGG-11.
- Landes, K.K. 1945. The Salina and Bass Islands rocks in the Michigan Basin: U.S. Geological Survey Oil and Gas Investigations Map 40.
- Lundstrom, S.C., K.A. Kincare, N.G. Grannemann, S. Yancho, D.R. Passino-Reader, D.P. Van Sistine, and J.C. Havens. 2003. Quaternary geologic framework of the Grand Traverse Bay region, Michigan: relationships to water, land, and ecological resources: *Geological Society of America Abstracts*, Seattle meeting.
- Michigan Department of Environmental Quality, 2003, WellLogic, Statewide Ground Water Database (SGWD): Lansing, Michigan, at URL <http://www.mcgi.state.mi.us/mgdl/?rel=thext&action=thmname&cid=2&cat=Drinking+Water+Wells>.
- Mozola, A.J. 1970. *Geology for environmental planning in Monroe County, Michigan*: Michigan Geological Survey Division Report of Investigation 13, 34 p.

- Mullins, H.T. and N. Eyles. 1996. Subsurface geologic investigations of New York Finger Lakes: implications for late Quaternary deglaciation and environmental change: Geological Society of America Special Paper 311.
- Neff, B.P. and J.R. Killian. 2003. The Great Lakes water balance: data availability and annotated bibliography of selected references: U.S. Geological Survey Water-Resources Investigations Report 02-4296.
- Nicholas, J.R., G.L. Rowe, and J.R. Brannen. 1996. Hydrology, water quality, and effects of drought in Monroe County, Michigan: U.S. Geological Survey Water-Resources Investigations Report 94-4161.
- Reeves, H.W., K.V. Wright, and J.R. Nicholas. 2004. Hydrology and Simulation of Regional Ground-Water-Level Declines in Monroe County Michigan: U.S.G.S. Water-Resources Investigations Report 03-4312.
- Sharpe, D.R., M.J. Hinton, H.A.J. Russell, and A.J. Desbarats. 2002. The Need for Basin Analysis in Regional Hydrogeological Studies: Oak Ridges Moraine, Southern Ontario: Geoscience Canada, v. 29, p. 3-20.
- Williams, V.S., G.I. Selner, and R.B. Taylor. 2003. GSMCAD: A CAD program for editing geologic maps and figures: 32-bit version revised Jan 14, 2003, U.S. Geological Survey Open-file Report 96-007.