PAPER

Observations of the Middle Island Sinkhole in Lake Huron – A Unique Hydrogeologic and Glacial Creation of 400 Million Years

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ABSTRACT

In the northern Great Lakes region, limestone sediments deposited some 400 million ybp during the Devonian era have experienced erosion, creating karst features such as caves and sinkholes. The groundwater chemical constituents of the shallow seas that produced these rock formations now contribute to the formation of a unique physical (sharp density gradients), chemical (dissolved oxygen-depleted, sulfate-rich) and biological (microbe-dominated) environment in a submerged sinkhole near Middle Island in freshwater Lake Huron. A variety of methods including aerial photography, physico-chemical mapping, time series measurements, remotely operated vehicle (ROV) survey, diver observations and bathymetric mapping were employed to obtain a preliminary understanding of sinkhole features and to observe physical interactions of the system's groundwater with Lake Huron. High conductivity ground water of relatively constant temperature hugs the sinkhole floor creating a distinct sub-ecosystem within this Great Lakes ecosystem. Extensive photosynthetic purple cyanobacterial benthic mats that characterize the benthos of this shallow sinkhole were strictly limited to the zone of ground water influence.

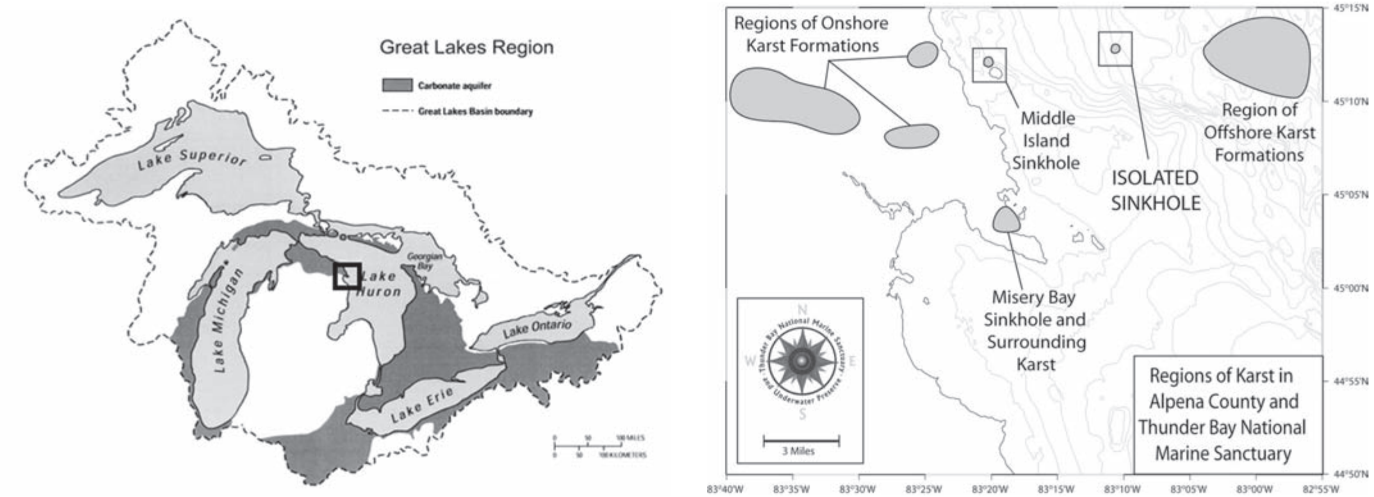
Introduction

Submerged karst features (sinkholes) were discovered in Lake Huron (Michigan) during a 2001 side scan sonar survey expedition conducted by the Thunder Bay National Marine Sanctuary (TBNMS) and the Institute for Exploration (Coleman, 2002). Our initial understanding of the composition of Lake Huron sinkhole systems is based on a preliminary 2003 ROV exploration of the Isolated Sinkhole located 10 miles offshore in the TBNMS at a depth of 93 m (Figure 1), revealing a visible cloudy layer attributed to groundwater. When compared to ambient lake water with a temperature of 3.9 °C and specific conductivity of 140 µS/cm, groundwater in these systems was observed to be several degrees higher in temperature, with 10-fold higher conductivity, 10-fold higher concentrations of chloride, and 100-fold higher concentrations of sulfate (Ruberg et al., 2005). A variety of non-photosynthetic benthic microbial mats were observed in this deepwater aphotic sinkhole system. Water samples collected from the sinkhole plume contained bacterial concentrations (~9x10^{9} cells l-1) an order of magnitude higher than ambient lake concentrations (~1x10^{9} cells l-1), and showed evidence for the occurrence of significant chemosynthesis in this lightless deep water environment (Biddanda et al., 2006). These rates of chemosynthesis occurring in the Lake Huron Isolated sinkhole were comparable to those measured in thermal vents in Yellowstone Lake (Cuhel et al., 2002).

Understanding the nature of the groundwater emerging in Lake Huron's sinkholes requires an introduction

FIGURE 1

Map of the North American Laurentian Great Lakes Basin showing regions of Silurian-Devonian aquifers potentially having karst formations (left, modified from Grannemann et al., 2000), and regions of above ground karst formations in Alpena County, MI and submerged sinkholes in the Thunder Bay National Marine Sanctuary (TBNMS), Lake Huron (right, after Coleman, 2002; Biddanda et al., 2006).

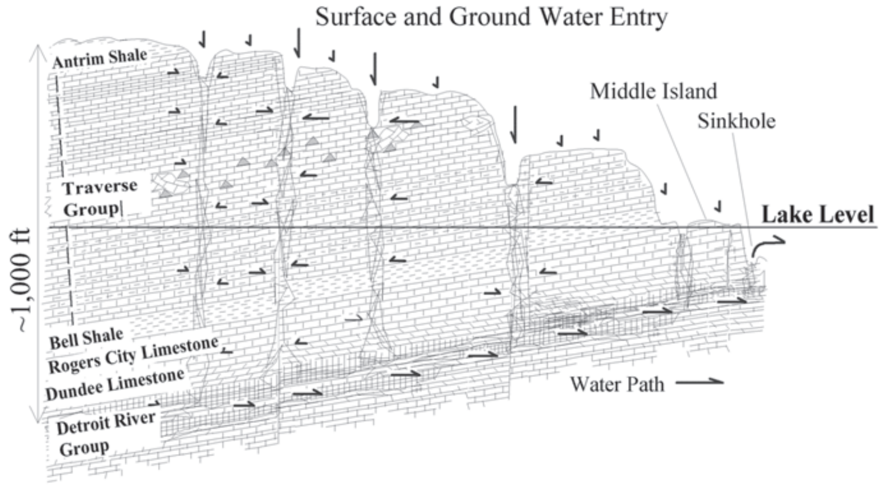


to the major geologic forces shaping sediments and lake morphometry in the Michigan Basin. Most noticeable are collapse features of the past 10,000 years since the glaciers retreated from the area. One of these, the Middle Island sinkhole/resurgence, is the surface expression of a collapse pipe extending down through the Rogers City and Dundee limestone formations into the top of the Detroit River Group karst system, approximately 200 feet below (Figure 2). Some inland sinkholes have collapsed through up to 800 feet of additional overlying formations not present at Middle Island (Black, 1983). Gypsum, anhydrite, and salts in the Detroit River Group formation were deposited in the Michigan Basin in the early Middle Devonian Period, approximately 400 million ybp (Gardner, 1974). Toward the end of this deposition there was a brief uplift and dissolution of some of the evaporites. Basin subsidence and new sediments buried and "fossilized" the karst features that had developed. This originally shallow and minor karst development would set the stage for large-scale dissolution and collapse in the recent one million year geologic history of Michigan's northern lower peninsula.

The large-scale loss of evaporites and collapse of the Detroit River Group and formations above it were caused by water flow. Surface and ground waters flowed into hydraulically open tectonic faults to deeply buried layers of the group. Surface and ground waters also penetrated the group where it is "exposed" at the edges of the Michigan Basin by glacial scouring. Water easily entered the partially developed paleokarst (fossil karst) systems and enhanced the karst as dissolution of the evaporites continued. As the evaporite volumes were diminished, the weight of overlying formations collapsed the group and caused structural adjustment faulting in the formations above, allowing more water to penetrate. For-

FIGURE 2

Schematic diagram of water sources and flow along subsurface pathways to discharge into Lake Huron. Inland recharge areas exert water pressure on aquifers, forcing water through the karst system to Lake Huron.



mations were weaker and were more likely to develop sinkholes where faults crossed each other.

Erosion had exposed the edges of formations before the last glacial period. Glaciation scoured the exposed surface of collapsed formations, sometimes filling in and plugging already developed sinkholes. As the glacier retreated, it left behind a cover of diamictite (glacial till) from zero to 700 feet that mantled bedrock and sinkholes, it left water available to surface streams and groundwater, and formations stressed by the removal of the glacial weight and crustal rebound. Some of the stress was relieved by collapse of windows into the karst system. If these windows were above the static water level (controlled by the Great Lakes levels of the time), water would enter the system at that point (Figure 2). If the window was below the static level, water was able to exit the system under hydrostatic pressure into the Great Lakes system, bringing with it the dissolved minerals and nutrients accumulated during its transit through the formations. The latter formations resulted in the submerged sinkhole systems that are the subject of our present study.

Sinkholes have been the source of scientific curiosity for many years in the northeast region of the lower peninsula of Michigan. Very near shore, a submerged sinkhole on Lake Huron in Misery Bay, northeast of Alpena, was first described in the latter part of the nineteenth century to be one or two hundred feet in diameter and 79 feet deep (Boulton, 1876). Farther offshore lies Middle Island sinkhole, a destination for recreational divers for at least the latter part of the twentieth century (Harrington, 1990). Remarkably, this is the first multi-disciplinary scientific study undertaken of this unique underwater ecosystem. The Middle Island sinkhole (45° 11.911' N, 83° 19.662' W; Figure 1) is located approximately 2 miles offshore at a depth of 23 m in NW Lake Huron. In the present study, a variety of methods including physico-chemical mapping, time-series measurements, diver observations and bathymetric mapping were employed to obtain a preliminary understanding of sinkhole features and to observe some of the physical aspects of the sinkhole system's groundwater interaction with Lake Huron.

Survey Procedures (Methods)

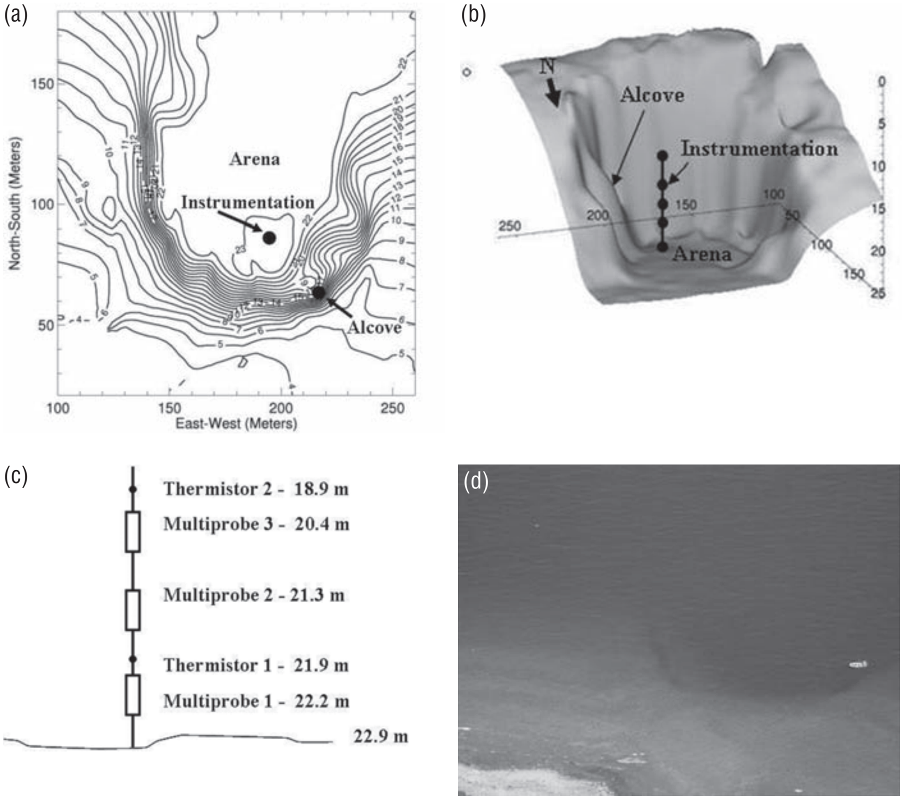
The project utilized divers from the NOAA TBNMS, NOAA Maritime Heritage Program, Noble Odyssey Foundation (NOF), State of Michigan, and East Carolina University. Their reports and drawings provided observations and measurements unobtainable from imagery, surface mounted acoustics or moored instrumentation. Dives were conducted from the TBNMS 41-foot R/V Huron Explorer, 28-foot R/V Sweetwater, and the NOF R/V Pride of Michigan. Trained chiefly in underwater archaeology, the dive team adapted readily to the range of skills required for this multi-disciplinary fieldwork. The result was an efficient, cost effective and safe acquisition of data. Prior to the dives, a SeaBotix LBV150SE ROV equipped with video and sensors providing observations of depth, conductivity and temperature was used to survey the layout and hydrological conditions of the entire sinkhole ecosystem.

Depending on assigned workloads, divers used either a single 80 ft.^{3} tank or twin 112 ft.^{3} tanks, resulting in average bottom times of 40 minutes. Maximum depths ranged from 9 meters to 22 meters, with water temperature averaging approximately 5 °C. Visibility underwater varied depending on the season, ranging from only 6 meters at times during the mid-to-late summer, to 20 meters or better in the spring and early summer. Diver tasks included mapping of the sinkhole "alcove" (a deep hole that fills with groundwater and spills over a sill into the wider sinkhole area) and "arena" (the wider bowl-shaped sinkhole area that opens out to Lake Huron) areas, deploying light scientific equipment, sample collection, and collection of still and video imagery (Figures 3, 4 and 5). Plan and profile views (Figure 5) of the sinkhole alcove were produced by diver observation and cursory measurements utilizing hand-held tape measures, a dive computer recording depth of water, and a compass to orient magnetic north. Observations were recorded on Mylar attached to a submersible plastic slate.

Bathymetric survey operations, time-series mooring deployments, and physical and chemical mapping were conducted from the NOF's 28-foot R/V Sounder, NOAA's R/V Huron Explorer and smaller vessels. The NOF bathymetric mapping system consisted of an Innerspace 455 single-beam echosounder with a 200 kHz 3° stainless steel transducer pole-mounted to the side of the R/V Sounder. The differential GPS unit linked to the echosounder was a Trimble DSM 232 with nominal +/- 1-5 meter accuracy. HYPACK® software was used to set up the survey grid and log and process the data. Sounding data were collected over the sinkhole area along east-west, north-south grid lines 5-10 meters apart. Lake conditions during bathymetric data collection were moderate with light winds and 0.3 meter waves. Maps of the sounding data were generated using interpolation and visualization methods

FIGURE 3

(a) Bathymetric contour map created from echosounder data points locating the alcove and the Instrumented Mooring used to collect time-series data in the arena (depth contours are in meters); (b) shaded surface plot (scale in meters) showing the location of instrumentation used to collect time-series data; (c) Mooring diagram showing arrangement of thermistors and multiprobes; and (d) aerial photo with Middle Island in lower left and 25 ft. Whaler on right near alcove. Temperature sensors were deployed from May 19 to September 17, 2007. The YSI6920 multiprobes were used to observe variability of conductivity, temperature, pH, and dissolved oxygen from June 15 to July 24, 2007.



available in IDL analysis software from ITT Visual Information Solutions (Figure 3a and 3b). The contour plot shows interpolated isobaths at 1 meter intervals. The shaded plot shows a shaded-surface representation of the interpolated data, rotated 200 degrees counterclockwise about the Z-axis.

Continuous time-series observations of water temperature in the Middle Island sinkhole during May 19 to September 17, 2007 were collected at 1 hour intervals using Onset UTBI-001 temperature sensors attached to a vertical mooring line at 1 meter and 4 meters from the bottom (Figure 3c). Sensor accuracy is 0.2°C over the range of 0° to 50°C with a response time of 5 minutes in water. Wind speed and direction were obtained from NOAA's National Data Buoy Center 3 meter discus buoy 45003 located approximately 40 km northeast of the study area at 45°21.02' N 82°50.40' W. The redundant R.M. Young Anemometers located 5 m above the lake surface provided hourly 8-minute averaged wind speed with a resolution of 0.1 m/s and accuracy of +/- 1.0 m/s, and wind direction with a resolution of 1.0 degrees and accuracy of +/- 10 degrees.

Continuous time-series monitoring of the groundwater–lake water interface in the Middle Island sinkhole in the arena was conducted at one-hour intervals from June 15 to July 24, 2007, using three multi-parameter sondes mounted at 20.4, 21.3, and 22.3 m below the surface on an anchored cable located at 45° 11.911' N, 83° 19.662' W (Figure 3). Depth to the sinkhole bottom was at 22.9 m. Each of the three YSI (Yellow Springs Instruments, Inc., Yellow Springs, OH) 6920 sondes were equipped with a temperature/conductivity sensor (6560), optical dissolved oxygen sensor (6150 ROX), and a pH/ORP sensor (6565).

To determine the thickness of the dense groundwater layer in the alcove and throughout the arena, and obtain physico-chemical measurements, a series of multi-parameter sonde depth profiles were performed. Water mass characterized by conductivity >2x of the Lake Huron water was considered to be groundwater. Profiles were taken beginning over the alcove and at approximately 20 m intervals extending to the north out into Lake Huron for 230 m. Depth profiles were taken using a YSI 6600 sonde equipped with sensors for temperature/conductivity, dissolved oxygen, and pH. Data was recorded onto aYSI 650 multi-parameter display at 2 second intervals.

Results and Observations

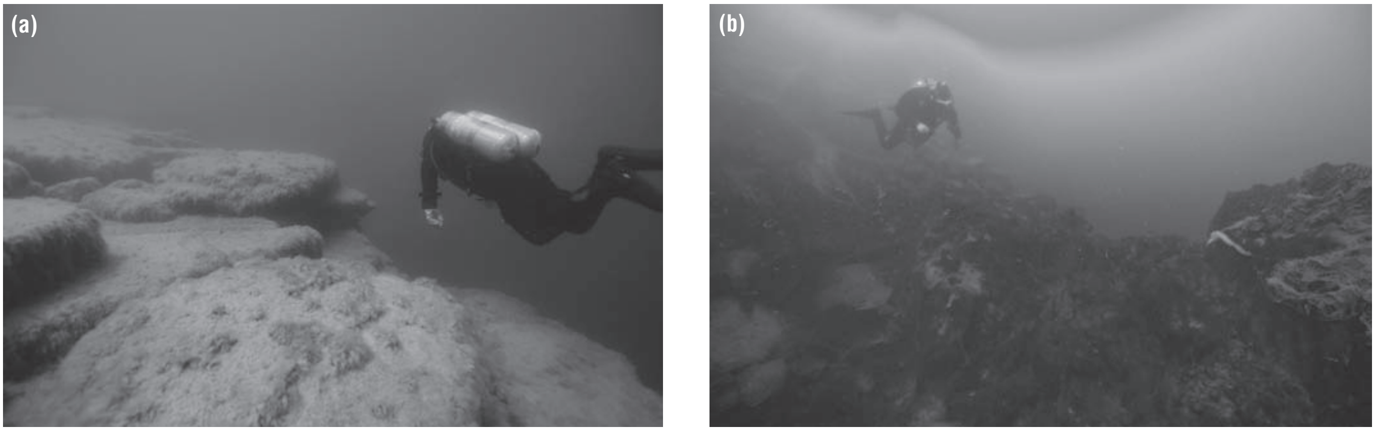
Diver Survey

Diver-collected imagery at a depth of 10 meters along the south edge of the Middle Island sinkhole shows the steep drop into the alcove below (Figure 4a). A partial wall between the alcove and the main arena of the sinkhole (Figure 4b) forms a reservoir of colder, denser groundwater that is maintained throughout the summer warming period.

A cloudy/shimmering layer of water at the thermo-pycno-chemocline (region of sharp changes in temperature, density and chemical composition of

FIGURE 4

(a) Southern edge of Middle Island sinkhole at a depth of approximately 10 m; (b) image taken from outside of the alcove, viewing rock wall (beneath diver) where groundwater contents (background) spill over into sinkhole arena (foreground).



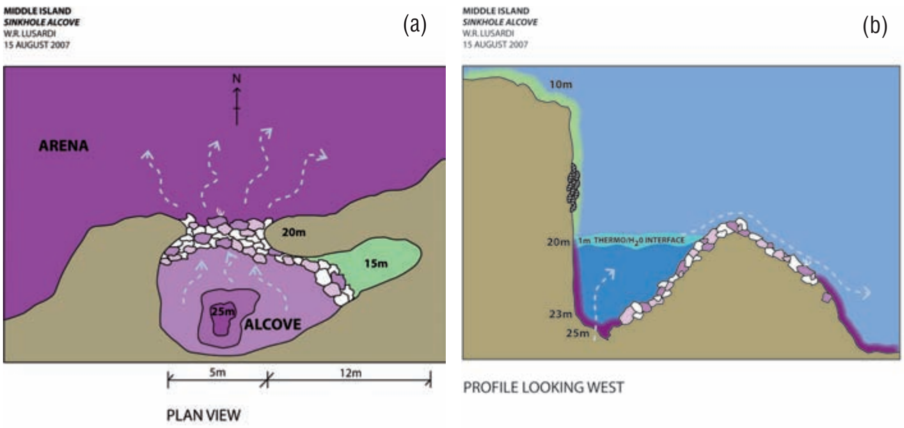
water; hereafter referred to as 'thermocline") was visible to divers while transitioning through surface waters into the alcove groundwater. The plan and profile views of the alcove and arena (Figure 5) represent a synthesis of visual and measured dimensions resulting in sketches that can only be created with divers present on the underwater site. Rocky fissures on the bottom of the alcove, at a depth of 22.5 m, provide a major conduit for groundwater to the sinkhole alcove and arena. The alcove fills to a level of approximately 5 m before spilling over the wall separating the alcove from the arena (Figure 4b and 5b). The sustained force of the flow is strong enough to propel divers over the top, and they are able to surf the relatively denser groundwater cascade (an "underwater waterfall") over the sill wall down-slope onto the arena floor. Water flow can be observed in the wafting motion of long strands of whitish sulfur-oxidizing bacteria living on the rocky surface at the interface between the sulfur-rich groundwater inside the alcove and the oxygen-rich lake water. Groundwater flowing out of the alcove then fills a shallow arena depression 23 m deep (Figure 3a) and gradually disperses throughout the sinkhole. Purple benthic microbial mats were observed along the walls and bottom of the alcove, along the wall separating the alcove and arena, and throughout the southern portion of the arena. Purple mats were only observed underlying the cloudy layer of water at the thermocline. This was particularly noticed in the alcove, where purple mats were not observed above the thermocline. Lake waters circulate through the sinkhole arena via the open northern side. This opening is believed to have resulted from wave and ice erosion beginning approximately 6,000 ybp (Hough, 1958) when lake levels were a minimum of 122 m lower than present. Lake Huron water levels began to rise from these low levels due to rebound of the earth's crust after the weight of glacial ice was removed at the end of the Wisconsin ice age during the Pleistocene epoch (Stanley, 1937).

Sensor Observations

While a thorough discussion and modeling of Lake Huron currents is beyond the scope of this present study,

FIGURE 5

(a) Plan view of the alcove indicating dispersion of groundwater into sinkhole arena providing nutrients to cyanobacterial mats. (b) Profile view showing the groundwater reservoir filling the alcove before spilling over wall into the Arena. The interface refers to the zone of thermocline/pyncnocline where groundwater and lake water meet.



NDBC buoy 45003 located 40 km NE of the study site provides some indication of the influence of wind speed and direction on the interaction of sinkhole groundwater with Lake Huron waters (Figure 6a). In general, winds with a southerly component tend to push warmer surface waters offshore through the open north end of the system which are then replaced with colder subsurface lake water. This wind-driven interaction between sinkhole groundwater and Lake Huron water is evident in the data obtained from temperature sensors suspended 1 m and 4 m height above bottom (hab) in the sinkhole arena (Figure 6b). Temperatures observed over the time period showed the warming influence of the groundwater on the sinkhole benthic region from Julian Day (JD) 139 to JD 150 (May 19 to May 30) while Lake Huron was still in the post-winter isothermal phase. During the warmer summer months, the groundwater tended to provide a cooling influence, but there appears to have been some periodic mixing likely associated with wave action. Data from the temperature sensors show that the groundwater at 1m hab resisted the thermal influence of warmer waters above (4 m hab), averaging 9.94 °C. During the period JD 170 to JD 260 (June 19 to September 17), water temperatures at 4 m averaged 11.75 °C. The influence of colder water during Lake Huron upwellings on JD 167, 170, 185, 192, 204, 208, 220, 222, and 234 was attenuated by the groundwater influence at 1 m. Brief periods of groundwater mixing with warmer waters above do occur as can be seen from the temperature response at 1m hab to the wind event lasting from JD 226 to JD 232 (August 14 to August 20).

Continuous time-series data from three multiparameter sondes measuring temperature, DO, pH, and specific conductivity deployed from June 15 to July 24, 2007 are presented in Figure 7. The placement of these instruments accurately depicted the layering of the groundwater at this location. The sonde at 1.5 m hab was located in the transition zone between groundwater below (0.6 m hab sonde) and lake water above (2.4 m hab sonde). Overall, the sinkhole arena groundwater layer, relative to lake water, was lower in temperature (typical), pH (7.3 vs 8.3), and DO (4 vs >11 mg/L), while higher in specific conductivity (1.7 vs 0.3 mS/cm). Throughout the monitoring period, groundwater characteristics were very consistent for most of the parameters except temperature which varied throughout the monitoring period. Temperatures fluctuated in all sondes; however, groundwater temperatures were often 4 °C colder than overlying lake water. Some sudden fluctuations in parameters may be explained by wind induced waves and currents interacting with overlying lake waters. Some significant events are observed on JD 170, 173, 179, 190, and 200 when higher winds with a southerly component (Figure 6a, starred) result in sudden, but temporary, changes in DO, conductivity, temperature and pH (Figure 7). These events result in higher oxygen and lower conductivity levels indicating a decrease in the thickness of the groundwater layer. However, ob-

FIGURE 6

(a) Wind speed and direction (6 hour averages) for the period May 19 to September 17, 2007 from NDBC Buoy 45003 located approximately 40 km northeast of the study area in northern Lake Huron; (b) Temperature observations obtained from Onset UTBI-001 sensors located 1 m and 4 m height above bottom (hab) at depths of 21.86 m and 18.86 m, respectively. Mooring was placed in the arena at 23 m depth during May 19 to September 17, 2007. An initial warming influence of groundwater during Lake Huron isothermal conditions can be observed JD139 to JD150 (May 19 to May 30). Vertical lines indicate period of sonde deployment.

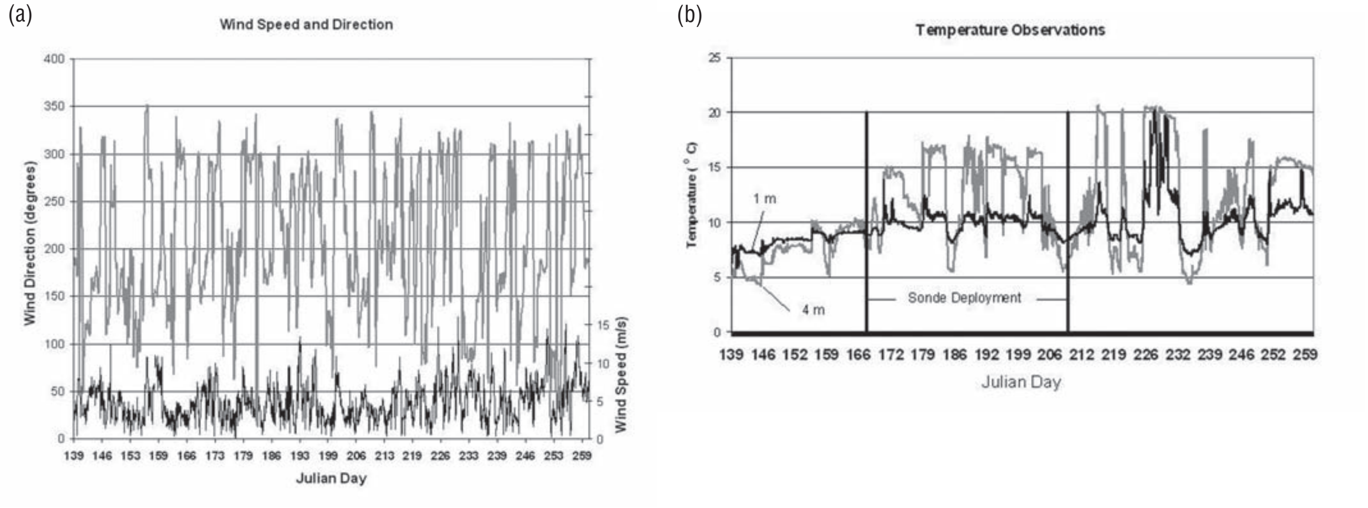
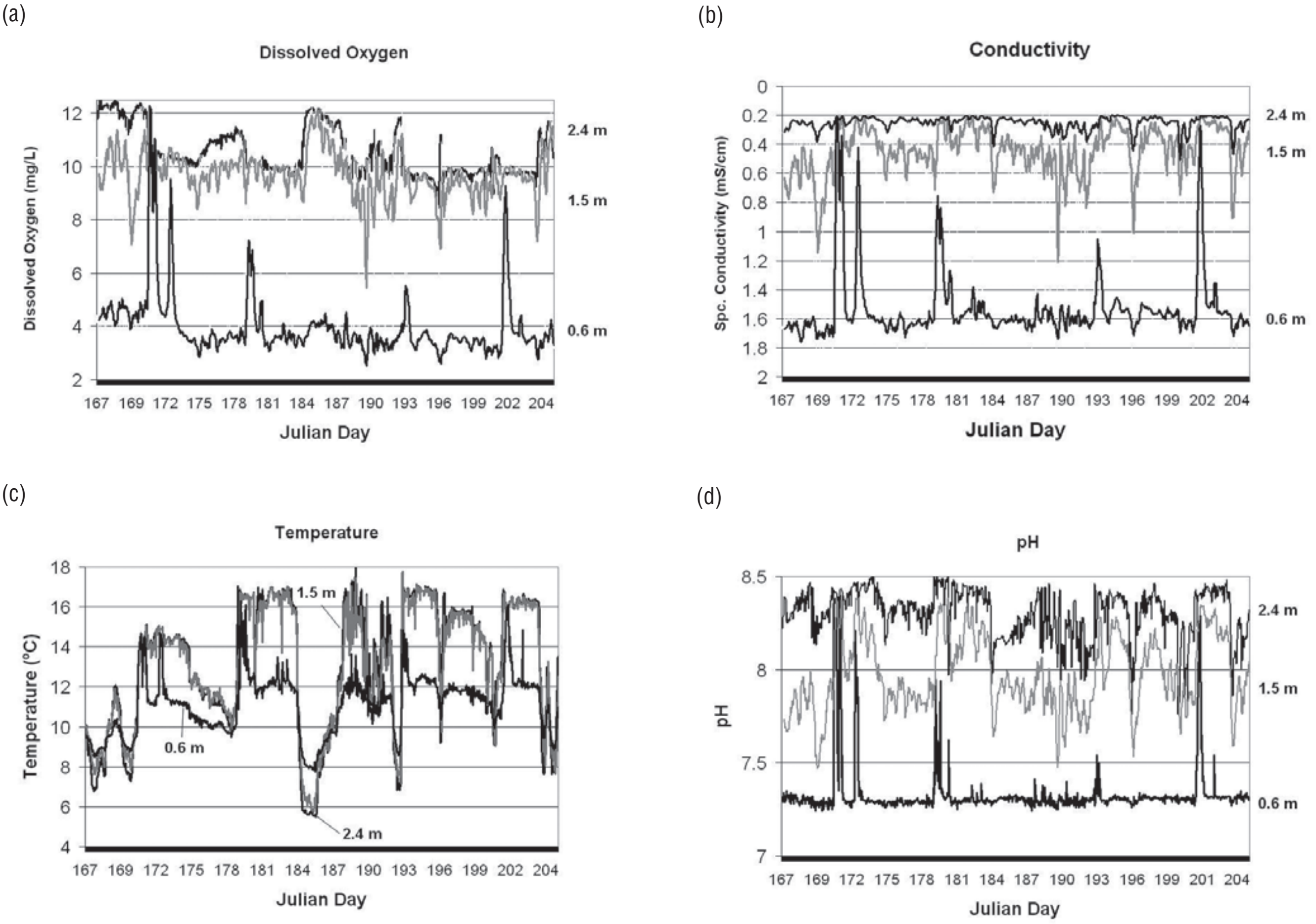


FIGURE 7

Dissolved Oxygen (a), Conductivity (b), Temperature (c), and pH (d) taken from sensors located in the arena at 0.6 m hab, 1.5 m hab, and 2.4 m hab during Middle Island Long-Term Monitoring from June 15 to July 24, 2007. Bottom at 22.8 m (hab=height above bottom).


(a)

(b)

(c)

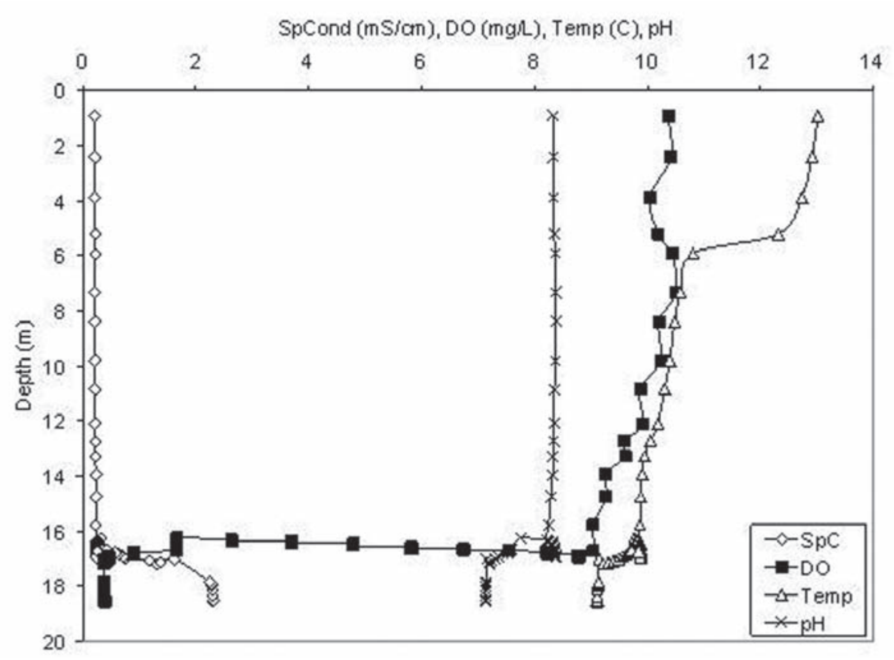
(d)

servations of lower oxygen and higher conductivity on JD 169, 184, 190, 195, and 203, indicating an increase in the thickness of the groundwater layer, appear to have little correlation with wind speed or direction. In addition to the parameters already measured, future time-series investigations must include observations of alcove groundwater flow speed, local rainfall, and ambient waves, temperatures and currents external to the sinkhole to adequately explain the interactions of sinkhole groundwater with overlying lake waters. Overall, groundwater temperature ranged 8-16 °C but was predominantly 10-12 °C and overlying lake water temperature ranged from 6-17 °C but was mostly 14-16 °C. These temperature data (Figure 7c) show a similar pattern as measured by the Onset sensors during the same period (Figure 6b).

To determine the thickness of the dense groundwater layer and to measure physico-chemical parameters, depth profiles using a multi-parameter sonde were obtained over the alcove and northward through the arena at ~20 m intervals (Figures 8 and 9). The alcove profile (Figure 8) shows that at about 16.5 m below the surface, specific conductivity rises from 0.2 to 2.3 mS/cm, DO drops from 10.4 to 0.4 mg/L, pH drops from 8.4 to 7.1, and temperature drops from 18.3 to 9.1 °C. While this alcove profile only extends to a depth of 18.5 m (Figure 8), the depth to bottom in the alcove is ~22 m, making the groundwater thickness approximately 5 m. This is slightly higher than the ~4.5 m height of the rock wall that separates the alcove from the arena (Figure 4b and 5). Together with diver observations discussed earlier, these data show that venting groundwater fills the alcove bowl and spills over into the arena (Figure 9). Groundwater thickness in the arena between 20 and 60 m along the transect averages 1.2 m, and then thins out to approximately 0.6 m thick which extends out to the end of our measurements at 229 m (Figure 9).

FIGURE 8

Depth profile of specific conductivity, dissolved oxygen, temperature and pH from lake surface to near bottom of alcove sinkhole on July 13, 2007. Alcove bottom at ~22.5m.



In the southern portion of the arena (close to the alcove), groundwater characteristics were different from the alcove mainly with higher DO (3-4 mg/L; Figure 9) and slightly lower conductivity (1.8 mS/cm). In the northern portion of the arena and beyond to a distance of 229 m, groundwater DO levels gradually increased to 6.5 mg/L (Figure 9). Overlying lake water in the arena at 12 m hab was characterized by higher DO (11.6 mg/L), temperature (10.2 °C), and pH (8.4), but lower specific conductivity (0.2 mS/cm). ROV/Diver observations and water mass characteristics confirm that the distribution of the purple cyanobacterial benthic mats was limited exclusively to the zone of groundwater influence. The groundwater emerging at the sinkhole likely provides a unique set of conditions that support the proliferation of purple cyanobacterial mats (Figure 9, 10).

Conclusion

The Middle Island sinkhole was formed by the collapse of the karst system roof forming a rubble pipe with a partially open top at this location. The collapse was coincidentally near the edge of the formation escarpment. The edge of the feature has been further modified by wave action and lake-edge ice-driven erosion into the escarpment face weakened by the presence of the sinkhole. This erosional process appears to have removed most of the northern wall of the sinkhole into Lake Huron before the lake reached its current elevation.

The source of the groundwater discharge could be from the natural hydrologic flow through the geologic formations and interacting with: 1) formation waters buried with the formation, or waters being squeezed out by compaction and lithification; 2) ground waters captured by the hydraulically open fault and fracture systems and released to the developing karst system; 3) under ice or melt water from the glaciers entering the system from the surficial sinkholes; and 4) post glacial (and perhaps some pre-glacial) meteoric and surface waters. The source(s) of the water, flow time, and flow routes are a complex puzzle, the resolution of which will require the

FIGURE 9

Schematic profile of sinkhole-lake cross section showing depth to groundwater and lake floor, approximate extent of purple mat (thickness not to scale; actual mat thickness is 1-2 mm), and groundwater DO along a 230 m transect extending from the alcove and northward through the arena on July 13, 2007 at the Middle Island Sinkhole. Groundwater thickness along this transect is approximately 5 m in the alcove, 1.4 m@40 m, 1m@60m, and 0.5m@100m. While maximum groundwater specific conductivity ranged between 1.7 and 2.3 mS/cm, a value that was 2x greater than the overlying lake water (i.e., 0.2 mS/cm) was used for determining groundwater thickness. Purple cyanobacterial mats occurred in areas with DO levels as low as 0.1mg/L up to 4 mg/L.

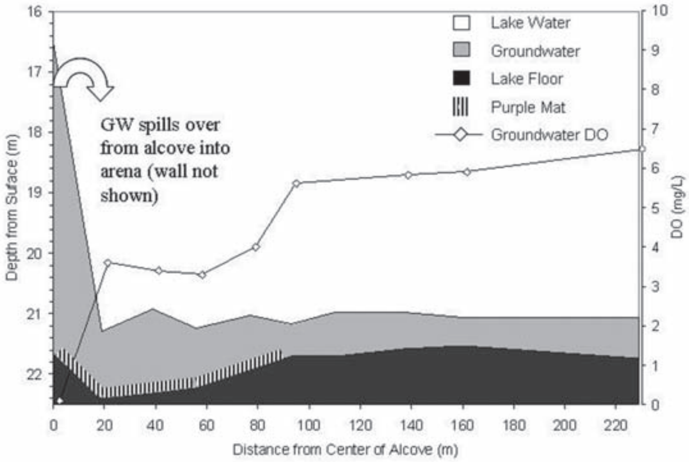
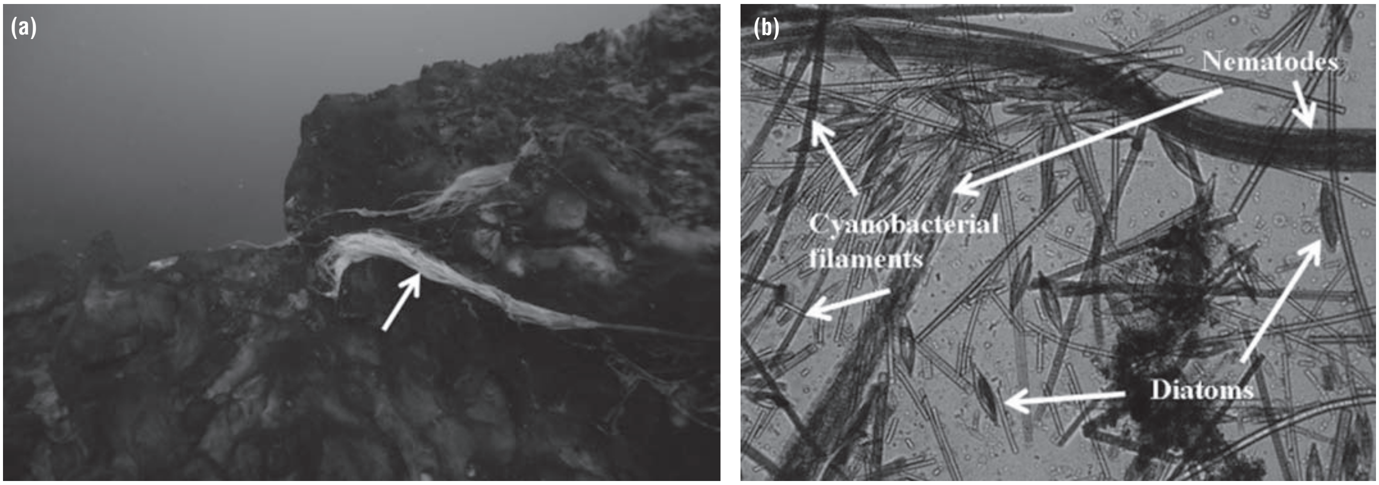


FIGURE 10

(a) Variety of benthic microbial mats inside sinkhole dominated by the purple pigmented cyanobacteria. Arrow indicates whitish strands of sulfur-oxidizing bacteria wafting in the flow of groundwater. The white filamentous sulfur-oxidizing bacteria occur at the interface between ground water (left) and lake water (right) where ground water spills from the alcove into the arena. (b) Microscopic image of diverse and abundant microbial cells and some metazoa in benthic mat material recovered from Middle Island Sinkhole.



application of geochemistry and isotope analysis to the spatial geology of the area. The very low levels of oxygen and high sulfate concentrations measured in the alcove water support the conclusion that the Detroit River Group aquifer is the groundwater source at the Middle Island sinkhole, as deeper aquifers tend to be more oxygen-depleted.

The filamentous cyanobacteria that form the extensive microbial purple mats observed by the divers and ROV are closely related to the genus *Oscillatoria* on the basis of microscopic and molecular studies (Figure 10). Periphyton such as diatoms as well as occasional metazoans such as nematodes are also observed under the microscope (Figure 10b). These predominant blue-green algae have two modes of growth; they can either perform oxygenic photosynthesis similar to green plants or, when sulfide is present, they can perform anoxygenic photosynthesis using sulfide as the electron donor (Stal, 1995). When growing in the presence of sulfide, they synthesize a different form of chlorophyll, causing pigments to be purple rather than green. Sufficient sulfide to support cyanobacterial growth is likely produced by sulfate-reducing bacteria in the groundwater-bearing sediments and the arena sediments on the lake floor. Sulfate is abundant in the groundwater (Biddanda et al., 2006), and organic carbon to fuel sulfate reduction is plentiful on the groundwater-impacted lake floor. Since cyanobacteria photosynthetically fix carbon dioxide, they can act as primary producers and may constitute the base of the food web in these unique ecosystems. Our observations in this and other shallow sunlit submerged sinkholes in the surrounding areas of Lake Huron confirm the presence of the purple photosynthetic cyanobacterial benthic mats whenever high conductivity, sulfate-rich ground water is present (Figure 10).

The occasional white bacterial strands attached to rocks at the alcove outfall are likely to be sulfur-oxidizing bacteria such as *Beggiatoa* (Figure 10a). These organisms oxidize sulfide in the presence of oxygen and deposit elemental sulfur within their bodies, giving them a whitish appearance (Dyer, 2003). Conditions for sulfur-oxidation are present in the sinkhole habitat where the oxygen-rich lake water mixes with the sulfur-rich groundwater. These long filaments are only found at the interface between groundwater and lake water (Figure 4b, 10a), further supporting these conclusions.

Questions regarding how the dominant cyanobacterial mats manage to disperse and colonize sinkholes that are small and geographically distant/isolated, as well as the significance of cyanobacterial mat production at the sinkholes to the surrounding lake food web remain to be addressed. Interestingly, the ancestors of the cyanobacteria that currently populate Middle Island sinkhole first appeared on earth approximately 3.5 billion ybp (Taylor, 1993), but are now being sustained by dissolved ions such as sulfates and carbonates deposited relatively recently (hundreds of millions of years ago). Another interesting feature of the submerged sinkholes is the abundance of organic-rich soft sediments found on site. Organic matter preservation may be favored in the sediments underlying water masses that contain high sulfate and low oxygen, as found in Lake Cadagno, Switzerland, which is fed by a subaquatic spring (Hebting et al., 2006). Based on the known widespread distribution of carbonate aquifer in the region (Black, 1983; Granemann et al., 2000), submerged sinkholes may be more numerous in the Great Lakes basin (Biddanda et al., 2006). These ecosystems could be important sites for biological production as well as carbon sequestration. The pursuit of such ecological enquiries in the future will be facilitated by the results of the first geophysical mapping of the Middle Island sinkhole reported here.

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