TECHNICAL NOTE

Groundwater Plume Mapping in a Submerged Sinkhole in Lake Huron

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ABSTRACT

A multidisciplinary exploratory project team from the Institute for Exploration, the Great Lakes Environmental Research Laboratory, Grand Valley State University, and the University of Michigan located and explored a submerged sinkhole in Lake Huron during September 2003. A CTD system and an ultra-short baseline (USBL) acoustic navigational tracking system integrated with an open frame remotely operated vehicle (ROV) provided high-resolution depth, temperature, and conductivity maps of the sinkhole and plume. Samples were also peristaltically pumped to the surface from a depth of 92 meters within and outside of the sinkhole plume. A 1-2 m thick cloudy layer with a strong hydrogen sulfide odor characterized the water mass close to the plume. Relative to ambient lake water, water samples collected within this layer were characterized by slightly higher (4-7.5 ^{o}C) temperatures, very high levels of chloride and conductivity (10-fold) as well as extremely high concentrations of organic matter (up to 400 mg C/L), sulfate, and phosphorus. Our observations demonstrated the occurrence of unique biogeochemical conditions at this submerged sinkhole environment.

INTRODUCTION

The Laurentian Great Lakes were formed about 10,000-12,000 years before present (ybp), and presently contain approximately 19% of the Earth's surface liquid freshwater (Beeton, 1984). The Lake Huron Basin is mostly covered with a layer of glacial till, sand, silt and clay. Underlying these sediments are aquifers formed within Paleozoic (Silurian-Devonian) bedrock. These bedrock aquifers were laid down when the shallow seas still spread widely over the continental areas approximately 350- 430 million ybp. The Silurian-Devonian aquifer consists of carbonate, shale, and sandstone matrix with some evaporite beds, and has fresh and saline water, which can contain varying amounts of sulfates, chlorides and iron. Dissolution of the Silurian-Devonian evaporites has produced the major karst features (Olcott, 1992) such as the sinkholes discovered during the 2001 acoustic survey expedition (Coleman, 2002) conducted by the Thunder Bay National Marine Sanctuary and the Institute for Exploration. The sinkhole vents, producing a visible cloudy layer above the lake bottom (Figure 1), were a serendipitous discovery made during a 2002 remotely operated vehicle (ROV) survey of the sinkholes. Recharge areas of freshwater replenishment for the Silurian-Devonian aquifers have been documented on land in the Lake Huron basin; these areas are typically sinkholes (Figure 2). In this report, we discuss the mapping of the Isolated Sinkhole located approximately 10 miles from shore at a depth of 93 m in the north central region of the Thunder Bay National Marine Sanctuary during September 2003.

Survey Methods

All survey operations were conducted on the 80-foot R/V *Laurentian*. The *Laurentian* is jointly operated by NOAA's Great Lakes Environmental Research Laboratory and the University of Michigan. A Seabird SBE-19 conductivity, temperature, and depth (CTD) recorder and LinkQuest TrackLink 1500HA USBL acoustic navigational system were integrated with the University of Michigan Hydrodynamics Laboratory's Benthos open-frame ROV (Figure 3). A peristaltic pump was used to pump water to the deck of the research vessel to collect water samples for laboratory analyses. The pump tubing inlet was attached to the manipulator arm and routed through the SBE 19 conductivity cell.

Instrumentation

The SBE-19 sensors included an internal-field glass conductivity cell with platinum electrodes (range: 0-7 S/m, accuracy: +/- 0.001 S/m), thermistor temperature sensor (range: -5 to +35 C, accuracy: +/- 0.01 C), and a mechanical strain gauge pressure sensor. The sensor system was attached to the lower ROV frame, as shown in the right-hand image in Figure 3, in order to collect data from just above the lake bottom.

Positioning System

The LinkQuest TrackLink 1500HA operates at 31– 43.2 kHz with a 120-150

FIGURE 1

Vertical gradient of 1-2m thickness resulting from sinkhole venting into ambient Lake Huron waters (photo from 2001 survey by ROV Little Hercules).

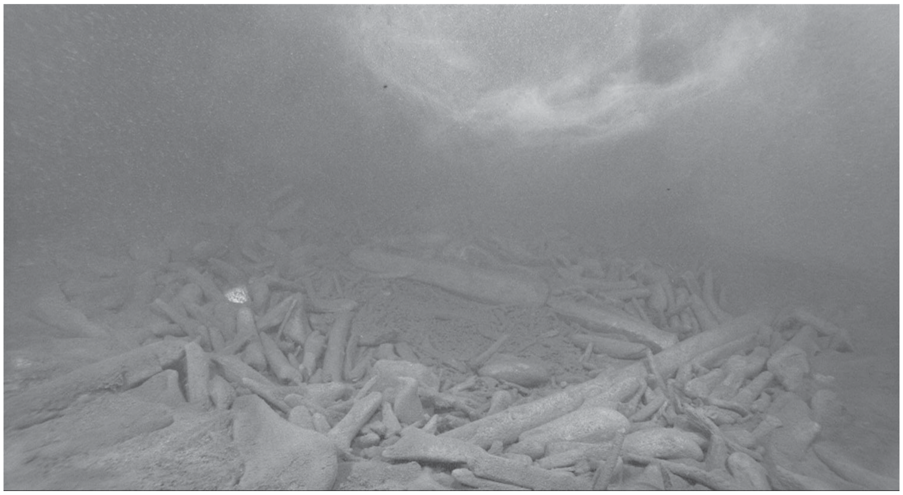
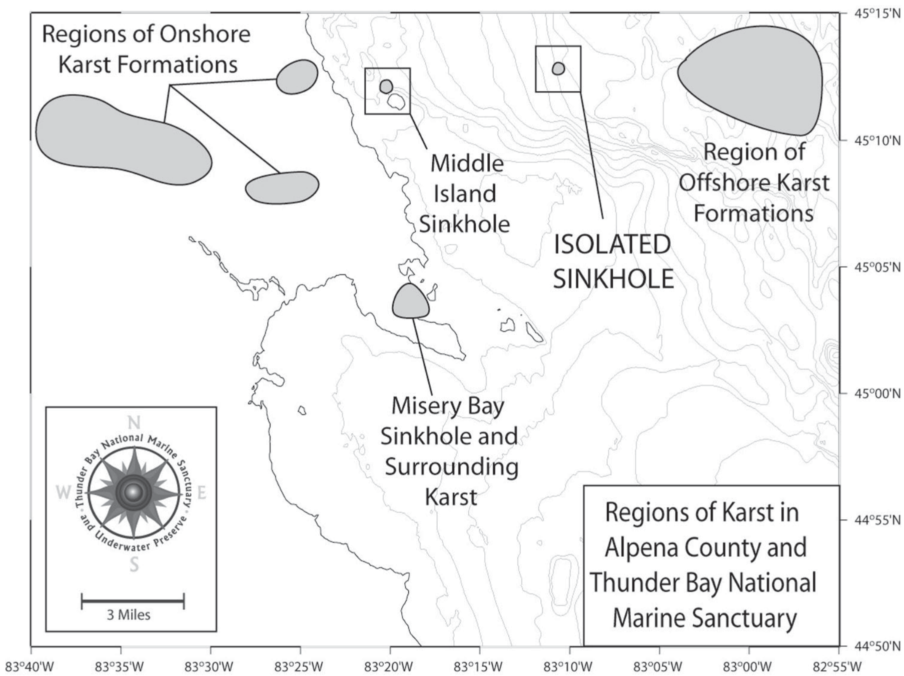


FIGURE 2

Regions of Karst in Alpena County and in Lake Huron



degree beamwidth and has a slant range accuracy of 0.2 m and positioning accuracy of 0.25 degrees. The surface unit was fixed-mounted to a mast attached to the vessel. The surface transceiver interrogates the transducer located on the ROV, receives the transducer uplink, and resolves position based on range and angle of incidence on the multi-element acoustic array. The positioning system software operates on a desktop computer and uses multiple inputs including the differential GPS signal (< 1m accuracy), a KVH fluxgate compass (+/- 0.5 degree accuracy) heading signal, and the output of the acoustic transceiver (slant range and bearing) to resolve underwater vehicle position. All signals from the positioning software were fed into HYPACK, Inc.'s HYPACK system, the primary navigational software used during this research cruise.

ROV

The University of Michigan's Remotely Operated Vehicle for Education and Research (M-ROVER) was the underwater experimental platform utilized for this investigation. M-ROVER is a Benthos Open Frame Sea Rover specifically designed to accommodate a wide variety of instrument packages including the Seabird CTD, selective sampling gear, and the LinkQuest Tracklink positioning system used in this sortie (Figure 3). Flexible tubing (3/8 in. I.D.) was attached to the ROV tether and run from the peristaltic pump on the deck of the R/V *Laurentian* to the M-ROVER located at the experimental site. The flexible tube was routed through the vehicle frame and into the CTD conductivity cell. Using the ROV's three function articulated arm to position the sampling tube, real time, selective sampling was conducted at several locations throughout the sinkhole. The Seabird CTD data was transmitted to the surface through spare conductor wires in the ROV tether. The M-ROVER is equipped with several autopilots that allow precise movement of the vehicle through the experimental arena. The ROV propulsion system includes four horizontal thrusters and two vertical thrusters in a vertran configuration. The thruster gain can be precisely controlled to diminish bottom disturbance. Precise navigation through the experimental area was accomplished using M-ROVER's 675 kHz, high resolution, color, scanning, imaging sonar. Detailed video observations were conducted with the ROV's onboard color video camera and all images were digitally recorded.

Chemistry Methods

Water samples from the deep region of the sinkhole were collected by pumping the samples to the surface via a peristaltic pump directly into acid clean bottles. Water samples from the ambient water column (lake water) were collected directly above the sinkhole, at depths of 5 m and 25 m, using teflon-coated Niskin bottles. All samples were immediately pro-

FIGURE 3

M-ROVER with tracking system visible on the starboard stern corner in the image at left and the CTD attached to the ROV frame in the image at right

cessed. For total phosphorous (total P), 50 ml of sample was measured into an acid-cleaned 70 ml Pyrex test-tube and then refrigerated until analyzed. Each sample was processed in duplicate with the average value recorded in Table 1. For chloride, water was filtered through a 0.2 uM Nylon filter and dispensed into a polypropylene test-tube, sealed tightly and stored in a refrigerator until analyzed. Total P and chloride concentrations were determined using standard automatic colorimetric procedures on an Auto Analyzer II as detailed in Davis and Simmons (1979). Total P was determined following digestion in an autoclave after addition of potassium persulfate (5% final conc.) (Menzel and Corwin, 1965). Sulfate concentrations were determined by ion chromatography (APHA, 1992).

Samples for particulate organic carbon (POC) were processed through pre-combusted (4h at 450°C) Whatman GF/F filters and frozen until analysis. Prior to analysis filters were thawed and soaked in 1.0N HCl and then dried at 80°C for 24h. Samples for dissolved organic carbon (DOC) were taken from the filtrate of the POC sample, after discarding the first 50 ml as a rinse, and poured into acid-cleaned and pre-combusted glass test-tubes and then frozen until analysis (Cotner et al., 2000). POC concentrations were determined on a Perkin-Elmer Model 2400 elemental analyzer. DOC concentrations were determined by high temperature combustion on a Shimadzu TOC 5000 carbon analyzer.

Survey Results and Observations

Visible Vertical Gradient (the cloudy layer)

An examination of *in situ* measurements using ROV mounted instruments and shipboard laboratory analyses of physicochemical conditions within the near bottom cloudy layer (Figure 1), and its comparison to lake water properties prevailing at a comparable depth in the lake away from the venting water showed that the venting water was characterized by distinctly unique properties (Table 1). Venting water was warmer than ambient lake water at depth only by a few degrees Celsius, but was characterized by 10-fold higher concentrations of chloride, 100-fold higher concentrations of sulfate, and 1000-fold higher concentrations of total P. High chloride concentrations are characteristic of the Silurian-Devonian aquifer (Olcott, 1992), and help explain the measured high conductivity. The high sulfate ion concentrations in the venting water could serve as substrate for sulfate reducers in this environment. Indeed samples from the cloudy layer smelled strongly of hydrogen sulfide (H_2S) when brought to the surface—suggesting anaerobic pathways of carbon transformations may be occurring in this sinkhole ecosystem. Furthermore, the significantly higher temperature prevailing in the venting water is likely to enhance microbial metabolism (Biddanda and Cotner, 2002), and thereby expedite biogeochemical cycling of bioactive elements in this near bottom environment.

Phosphorus (P) concentrations in the venting water were 1000-fold higher than the ambient lake water. Because P is commonly the limiting nutrient for primary productivity in all of the Laurentian Great Lakes (Schindler, 1977; Fahnenstiel et al., 1998), the input of P into Lake Huron from sinkhole discharges may be of significant local importance in terms of water quality as well as overall productivity. However, such P entering the lake via submerged sinkholes at aphotic depths (as in the present study at 93 m), will have to become mixed into the surface sunlight layer over days to months before it can influence autotrophic primary production by phytoplankton. A thorough quantification of such nutrient fluxes from sinkhole discharges to the Lake Huron P budget and its ecological consequences within the Great Lakes opens the possibilities for future investigations.

Coincident with the presence of high concentrations of dissolved nutrients, the venting water was characterized by 5-fold higher concentrations of DOC and 400-fold higher concentrations of POC, relative to ambient lake water. Both DOC and POC are utilized by heterotrophic bacteria, to fuel the microbial food web in aquatic environments (Cotner and Biddanda, 2002). Such high abundance of organic matter prevailing in the sinkhole plume appears to be the result of localized but intense bacterial chemosynthesis and heterotrophic production processes occurring at this submerged sinkhole ecosystem within the Lake Huron basin (Biddanda et al., in preparation). The combination of high abundance of inorganic nutrients and organic matter provides the context for both aerobic and anaerobic bio-

TABLE 1

A comparison of ambient Lake Huron water and sinkhole vent water (see text for explanations).

Parameter (Units)	Lake Water	Vent Water
Conductivity (µS/cm)	140	1700
Temperature (°C)	3.5	7.0
Chloride (mg/L)	13	175
Sulfate (mg/L)	16	1457
Total P (mg/L)	0.004	3.230
DOC (mg/L)	2.5	9.8
POC (mg/L)	0.9	405

FIGURE 4
Depth map of sinkhole vent plume

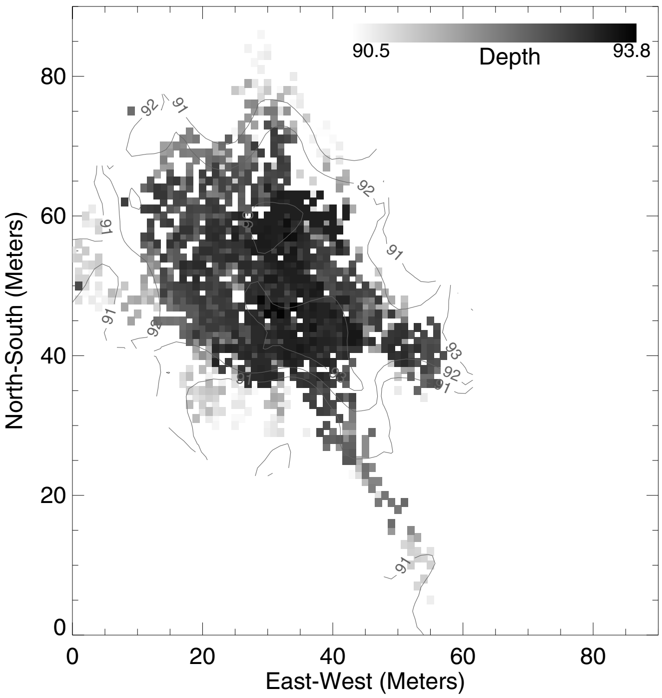
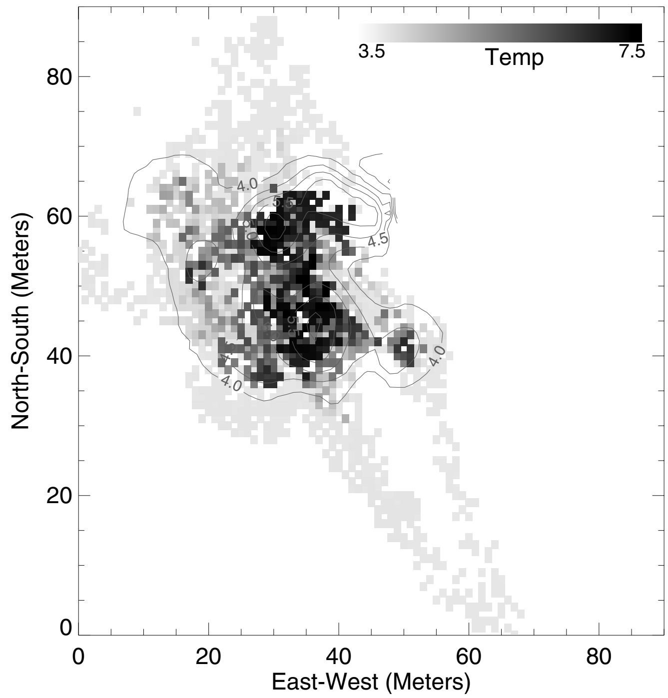


FIGURE 5
Temperature map of sinkhole vent plume



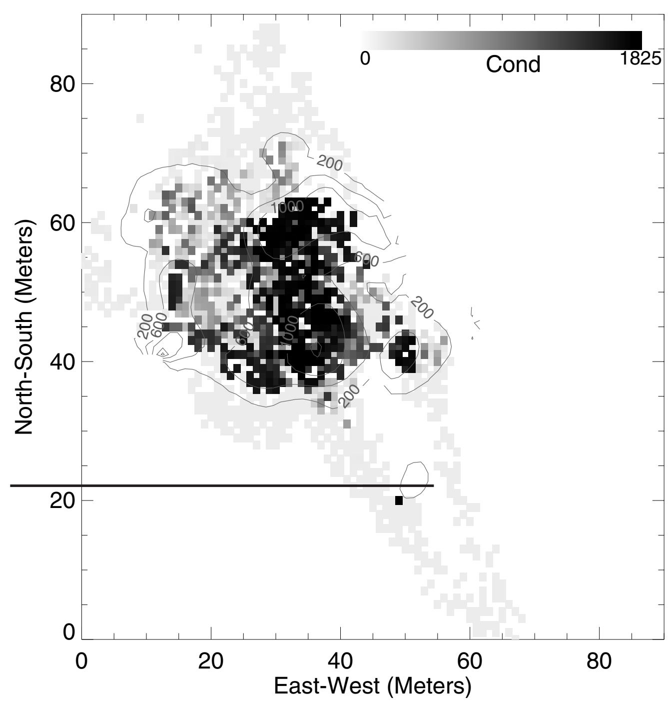
geochemical processes to occur within the sinkhole environment, which may explain the visibly cloudy nature of the venting plume.

Depth, Temperature, and Conductivity Maps

Temporally referenced CTD and acoustic positioning data, in the Universal Transverse Mercator (UTM) format converted to a local reference in meters, were merged to create figures 4, 5, and 6. IDL (Research Systems, Inc.) was used to plot contoured visualizations. The vertical and horizontal axes of each plot are in meters. The temperature and conductivity data were filtered and depth-averaged providing observations at about 1 meter above the floor of the sinkhole. Median filtering, a non-linear technique that applies a sliding window to the data sequence, was used to eliminate any spurious noise in the data.

The dimensions of the sinkhole from the depth map (Figure 4) are approximately 55 meters by 40 meters. The depth range from the deepest point in the sinkhole to the surrounding lake depth is approximately 3 meters. The

FIGURE 6
Conductivity map of sinkhole vent plume



depth map indicates the existence of two deeper sections of the sinkhole; one on the northeast rim and a second area separated by a low ridge (approximately 1 meter) about 20 meters to the south. Both areas appear to be sources of plume water as observed from the temperature and conductivity maps (Figures 5 and 6). Currents could contribute to other areas of increased temperature and high conductivity that do not appear to coincide with increased depth. The temperature map covers a range from 3.9°C to 7.5°C. Conductivity map values range from 122.6 uS/cm to 1821.2 uS/cm. The high conductivity of the plume is attributed to the high levels of Chloride and Sulfate.

The temperature of the plume water appears to come into thermal equilibrium with the larger mass of surrounding lake water more quickly than mixing can dilute the highly conductive plume waters. Normal temperatures in the Great Lakes at these depths are typically 4°C. The chemistry results (Table 1) and high conductivity levels measured during this preliminary investigation appear to indicate that the source of the sinkhole plume is the Silurian-Devonian aquifer.

Future Work

Complex linkages existing between surface water and groundwater driven by hydrologic and climatic conditions may influence both the flow rate and composition of groundwater venting in karst sinkholes (Gibert et al., 1994). Future plans include a continued exploration and survey of nearshore and deeper-water sinkholes comparing chemistry and microbial parameters. Further investigations will be done to determine the age of groundwater in various sinkholes throughout this karstic system. The deployment of instrumentation in the Isolated Sinkhole measuring flow, light, dissolved gasses (e.g., oxygen, hydrogen sulfide), temperature and other parameters will provide insight into seasonal/annual variability.

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