LakeNet: An Integrated Sensor Network for Environmental Sensing in Lakes

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Keywords: sensor network, lake, limnology, diurnal fluctuation

Abstract

Field investigations in the hydrologic sciences often are limited by the ability to collect data at the high spatio-temporal resolution necessary to build accurate predictive models or to control complex engineered systems in real-time. Here, we describe LakeNet, an embedded wireless sensor network constructed by an interdisciplinary team of hydrogeologists, environmental engineers, and electrical engineers at the University of Notre Dame. Off-the-shelf temperature, dissolved oxygen, and pH probes are suspended from floating, waterproof cases with electronics, forming sensor pods. Wireless transmission to relay stations and an embedded PC gateway will enable researchers to interact with the network remotely to alter sampling patterns, download data, and analyze data trends using the gateway's recursive processing of raw data. LakeNet will also function as a 'smart' network in which each pod's system is aware of the others and in-network computation detects change points in the data stream, thus triggering an altered sampling strategy in response to sensed events or individual probe/pod failure. This ability for the sensor network to alter sampling strategy can increase sensor shelf life, which will become more important as novel sensors are developed, and decrease system energy requirements. Initial deployment at St. Mary's Lake on the Notre Dame campus in the fall of 2005 showed that temperature, pH, and dissolved oxygen changes were consistent with diurnal fluctuations in sunlight, hence photosynthesis. In describing LakeNet, we summarize current capabilities and ongoing research, including some of the challenges that need to be overcome for further sensor network development, widespread deployment, and maximum usefulness.

Keywords: sensor network, lake, limnology, diurnal fluctuation

Introduction

Managing our freshwater resources, both for human needs and ecosystem health, is becoming increasingly important as the world's population continues to grow. The lack of adequate clean freshwater supplies adversely impacts many portions of the Earth, threatening quality of life as well as economic progress. As evident from the devastating New Orleans flood that followed Hurricane Katrina in 2005, weather extremes can pose particular challenges to management of freshwater resources and can have widespread human and ecological consequences. Extreme events, whether they bring too little or too much rainfall, can be compounded by factors such as loss of wetlands, deforestation, development in watersheds or on floodplains, overgrazing, etc. According to the United Nations (Lenton *et al.*, 2005), an estimated 1.1 billion people worldwide lack clean drinking water and 2.6 billion lack access to basic sanitation. Hence, 2005-2015 was designated the International Decade for Action: "Water for Life." Clearly, the international community has recognized that water distribution must be carefully monitored and controlled in terms of water quality and quantity.

The 2001 Global Water Cycle Report (Hornberger, 2001) identified as one of the necessary ingredients for understanding (and hence better managing) the water cycle: "improved observations, including innovative measurements using new technologies and networks for coordinated observations." The need for well-coordinated, 'continuous' monitoring of surface waters has long been recognized. For example, the U.S. Geological Survey's hydrologic benchmark station program has greatly benefited researchers and society for over 40 years by providing hydrologic data often coupled with water quality data on ‘benchmark’ streams. New technologies can build upon such long-term successes by providing relatively inexpensive, coordinated, intelligent networks. As described by Lemmon and Montestruque (2006, EES, this edition), embedded networks are an emerging technology that ‘embeds a computational intelligence in the environment that allows adaptive monitoring and control of that environment.” Environmental sensor networks therefore may provide a key element for better understanding and managing the water cycle. Environmental sensor networks for a variety of applications have been proposed and/or are being developed (e.g., Vivoni and Camilli, 2003; Szewczyk *et al*., 2004; Delin *et al*., 2005; and other papers in this issue), but deployment of sensor networks in surface water environments is in its infancy.

Here, we describe development and test-deployment of LakeNet, an integrated sensor network for environmental sensing in lakes and wetlands that focuses on lake water quality. In this network, sensors become an integrated component of their aqueous environment throughout data collection, and data are communicated between pods and back to researchers remotely using radio waves. At the proof-of-concept stage, as described here, we deployed a small-scale network for a 10-day test period. In addition to describing the development and initial deployment of LakeNet, we describe ongoing and future research, including some of the challenges that need to be addressed short- and long-term.

Methods

Sensor Pod Design

For this initial deployment of a lake sensor network, we were interested in studying diurnal fluctuations in pH, temperature, and dissolved oxygen in freshwater lake systems. Sensor data needed to be gathered at 10-15 minute intervals, and data collection had to be automated and the data easily retrievable at the end of the observation period. The experimental design therefore required an embedded sensor network constructed of components that were watertight and robust to temperature fluctuations. Off-the-shelf sensor probes purchased from Global Water Instrumentation, Inc. (Gold River, CA) made it possible to measure the three parameters of interest as voltages. Our job was to provide the sensors with watertight encasement, including electronics as described below (hereinafter, each watertight encasement with its associated probes and electronics is called a 'pod'), that allowed them to be left in the environment for an extended period and that permitted data to be communicated wirelessly.

LakeNet sensor pods were assembled from commercially available components with some custom circuitry. The heart of the LakeNet sensor pod's electronics was the MICA2/MDA300 modules manufactured by Crossbow Technology, Inc (San Jose, CA). The MDA300 is a small data acquisition module that is connected to the three sensor probes, while the MICA2 is a radio/processor that is interfaced with the MDA300. These components were selected because they had been successfully used in other embedded sensor networks. The MICA2 comes equipped with an antenna and radio transmitter using a frequency of 433 MHz. FCC regulations limit the power of unlicensed radios, and for the MICA2, this limits the maximum communication distance to 30 m. Greater distances can be covered by placing relay nodes between the sensor pods and the user. Ultimately, an embedded PC gateway will allow researchers to issue commands and to collect data remotely using the internet; however, for this deployment a gateway node, responsible for issuing sampling commands, was connected to a laptop and transported to the field site at least once a day throughout the deployment in order to retrieve data.

In order to prolong pod lifetime, a sensor interface board was built that provides the ability to turn the sensor probes off automatically between sampling intervals in order to conserve battery power. This is an extremely important consideration because the MDA300, while it can source at most 5 volts, is powered by the battery of the MICA2, which usually only provides 2000 mA-hr of current at 3 volts. This is much less than is required to drive the sensors, which use a 12 volt battery.

Another important consideration is that the pods be robust to environmental conditions, while remaining buoyant enough to prevent the antenna on the MICA2 from being submerged and blocking radio transmission. First and foremost, in an aqueous environment it is critical that the sensitive electrical components be protected from moisture, including condensation. In addition, these components need to be secured and sheltered from movement associated with waves, wind, or jostling during transport and deployment. A prefabricated solution that addresses each of these concerns is not commercially available; however, it has been possible to modify existing products to meet our needs. A water-tight OtterBox® (Otter Products, LLC; Fort Collins, CO), purchased and altered by drilling holes for the sensor wires and the antenna, provides protection from water and impact. The box also comes packed with foam that can be cut to fit the components, providing stability and preventing movement as shown in Figure 1.

The holes for the wires are sealed with marine sealant, and the box, which is already buoyant, is stabilized and made to float higher in the water by forming a floating ring from a child's pool toy composed of closed cell polyethylene foam. This pool toy, commonly referred to as a 'Noodle,' is a tube with a cylindrical hole down the center. Nylon rope is threaded through the hole, pulled tight, and knotted once the tube has been formed into a life-preserver-like ring around the box. This ring is shown in Figure 2a along with the pod and sensor probes during deployment. The free end of the rope is then tied to a cinder block or other heavy object in order to anchor the pod in place after it has been deployed. Just prior to deployment, commercially available silica gel desiccant beads (Miracle Coatings; Newport Beach, CA) were added to absorb water and prevent the build-up of condensation. Figure 2b is a photograph showing a pod in St. Mary's Lake.

After this system capable of collecting and transmitting data had been developed, it was then necessary to consider what its field lifetime would be. Ideally, it will be possible to put wireless sensor networks into the field for months, or even years, during which data are continuously collected and little maintenance from the researcher is required. Currently, each pod has two D cell batteries to power the MICA2/MDA300, as well as a 12 volt marine battery to power the three sensor probes. At most, these batteries can provide enough power to collect data for about two weeks. However, batteries are sensitive to the temperature variations that are an inherent characteristic of fieldwork, and lower temperatures reduce battery life even further. The limited field life of these pods is a concern and will be the focus of future modifications, as discussed later in this paper.

Test-case Sensor Network Design

When a command is issued from the gateway attached to the laptop, that command is propagated through the network, allowing the pods to determine the strongest connection between neighboring pods and thus where their data should be sent. In most cases for a deployment of this size, communication occurred directly between the gateway and each individual pod; however, occasionally it was not possible for a pod to establish a direct connection to the gateway due to weaknesses in network connectivity as a result of temperature, humidity, time of day, etc. Under these environmental conditions, data were relayed from pod to pod until reaching the gateway laptop. The flexibility of the network software is such that the network routing table is rebuilt each time connections are established between the gateway and the pods. The software also adaptively switches the data route to find those pods with the best connectivity, allowing data to be transported to the gateway from pods that are too distant to hear the gateway directly. A schematic illustrating communication between pods and between pods and the gateway is shown in Figure 3.

Location Description

St. Mary’s Lake on the University of Notre Dame campus was selected as the testbed for the LakeNet project. The proximity of this site facilitates the development and deployment of such an interdisciplinary project and allows problem-solving and modifications to be performed with greater ease. Our ongoing research interests focus on the trigger mechanisms associated with algal blooms in this small eutrophic lake, as well as photochemical oxidation reactions responsible for degrading dissolved organic matter present in the lake. In order to characterize the major element concentrations of St. Mary’s Lake, water samples were collected from a site near the location of the LakeNet deployment and analyzed using a Perkin Elmer Optima 3380XL ICP-OES. The results are shown in Table 1.

Test-Case Deployment

In late October – early November 2005 a total of 8 pods were deployed over a four day period. Depending upon their deployment dates, the pods were left in the field for a minimum of 6 days with some pods in place and collecting data for 10 days. The pods were anchored about 10 m from shore in a shallow region of the lake where depths were no more than 1.3 m. The depth of the sensor probes during this trial was fixed at about 0.3 m beneath the lake surface, but this depth can easily be adjusted during future deployments. The pods were deployed in two rows: within each row the pods were roughly 2 m apart, and there was about 1 m between the two rows. A general schematic of the deployment is visible in Figure 4 and a photograph taken during the deployment is shown in Figure 5.

Calibration

Data are measured by the probes and recorded by the MDA300 in terms of voltages. It is therefore necessary to calibrate each probe so that the measured voltages can be converted into units of interest using the calibration curve equation for each individual probe. Calibration was conducted both before and after deployment of the pods in St. Mary's Lake. pH probes were calibrated using pH 4.0, 7.0, and 10.0 standard solutions, and temperature probes were calibrated using an ice water bath (~0^{o}C), tap water (~19^{o}C), and heated water (~45^{o}C). We used a 0% dissolved oxygen standard solution described in *Standard Methods for the Examination of Water and Wastewater* (1995), consisting of copper sulfate with a trace amount of cobalt chloride. Our

100% dissolved oxygen solution was simply well-aerated tap water at room temperature. The probes were allowed to equilibrate in each solution for a minimum of 15 minutes with data collected every minute. The calibration curves were created using the data recorded for five minutes after equilibration had definitely been achieved. The equation for the calculated line-of-best-fit ($R^2 \geq 0.96$) was determined from the calibration curves, and the voltages obtained in the field were put into the calibration equation, yielding actual values for pH, temperature, and dissolved oxygen.

Results and Discussion

The primary objective of this deployment was to test the design of both the pods and the network under field conditions and to examine its ability to collect data continuously and reliably for an extended period. At a minimum, continuous data were collected for just over 6 days, with a maximum of almost 10.5 days. On average, each of the eight pods was able to collect data for 8.3 days. This limited lifespan is primarily a function of the 12 volt battery powering the sensor probes. Of the eight pods, all of them except one were able to collect and transmit data for each of the three parameters (temperature, pH, and dissolved oxygen). The one failure was an inability to collect temperature data, likely due to a loose connection. However, after calculating actual values using the calibration curves, it became obvious that values from several of the probes were not reasonable, with erratic data either from the start or at some point along the sampling period. Since this was an initial deployment, there may still need to be fine-tuning of the electronic connections, although we also believe that some of the probes might have been faulty from the start. Sampling probes can also experience difficulties because of clogging or biofouling, and this is always an issue when conducting field studies. In any case, our initial deployment suggests that it is important to test sensors, pods and a network thoroughly at a convenient location before installing at a remote site.

Data for the local weather conditions during this deployment were obtained from www.weather.com, which provides several months worth of daily high/low temperatures and precipitation for a given zip code. The high and low air temperatures for each day are shown in Figure 6. High temperatures ranged from 9 to 21^{o}C; lows from -2 to 11^{o}C over the study period. The fairly large spread in air temperatures, from below freezing to above 20^{o}C, indicates that this test deployment was subject to a broad range of conditions as might be expected in the temperate zone excepting the height of summer and winter. Measurable rainfall occurred during four days of the deployment. 13.7 mm fell in the evening of 31-October into the early morning of 1-November, 0.8 mm fell late in the afternoon of 5-November, and 7.4 mm fell throughout the day on 6-November.

An example of the data collected by the temperature probes is shown in Figure 7. Diurnal fluctuations are evident with maxima in the late afternoon (roughly 3-5 PM) and minima in the midmorning (roughly 9-11 AM). Similar trends were observed in the temperature data from the other sensor pods. The water temperature range between the daily maxima and the daily minima averaged about 1.1^{o}C for all of the operating temperature probes. There was no correlation observed between air and water temperature daily highs, but there appeared to be a weak positive correlation between daily air and water temperature lows measured by three of the pods (R^2 = 0.2987, 0.3052, 0.4492).

The data collected from the pH probes showed that pH generally was between about 8.0 and 8.8, with pH maxima in the late afternoon (roughly 3-5 PM) and minima in the morning (roughly 8-9 AM) as exemplified by Figure 8. In addition, note the decrease in pH on 1-November perhaps due to rainfall; the South Bend area receives acid rain.

The dissolved oxygen data show a similar diurnal fluctuation to the temperature and pH data with maxima in the late afternoon (roughly 2-5 PM) and minima in the morning (roughly 7-9 AM) as shown in Figure 9. The fact that the data go above 100% dissolved oxygen could be a calibration problem. A more precise method for calibrating the dissolved oxygen probes is being developed; however, it is still possible to compare the range of data collected by the pods. Throughout the course of a day, dissolved oxygen varies by about 28 percentage points ± 5, on average. In general, we saw no obvious effect of rainfall on dissolved oxygen.

Overall this preliminary deployment was successful, and data collected by the temperature, pH, and dissolved oxygen probes clearly showed diurnal fluctuations with maxima later in the day. The fact that air and water temperature highs and lows showed little or no correlation over this short study period is not unexpected. Changes in water temperature are known to occur very slowly as a result of the high specific heat and high latent heat of evaporation of liquid water. It is instead likely that the observed temperature maxima in the late afternoon are a result of solar radiation striking the water as a large component of the sun’s light energy is absorbed and transformed to heat within the first meter (Wetzel, 2001).

The observed maxima of pH and dissolved oxygen in the late afternoon are likely explained by the photosynthetic activity of phytoplankton in this eutrophic lake. Through the reaction of carbon dioxide and water, photosynthetic organisms produce organic carbon and oxygen according to the reaction:

$6CO_2 + 12H_2O \rightarrow C_6H_{12}O_6 + 6H_2O + 6O_2$.

This reaction consumes CO_2, which decreases the carbonic acid concentration and hence increases the pH. CO_2 and carbonic acid are linked according to the reaction:

$CO_2 + H_2O \leftrightarrow H_2CO_3$.

Thus, both dissolved oxygen and pH were observed to increase in the late afternoon when photosynthetic organisms have a peak in activity. It should be noted that less oxygen can be dissolved in warmer water than in colder water. Therefore, if temperature were the dominant factor regulating the amount of oxygen in solution, the opposite trend would have been expected (Wetzel, 2001). Similar trends in diurnal fluctuation of pH and dissolved oxygen have been well documented and explained by previous researchers (Wetzel, 2001). The fact that the LakeNet data are consistent with the documented behavior of many eutrophic lakes serves to validate the capabilities of the LakeNet system.

Ongoing and Future Research

As a concept, we have shown that LakeNet can adequately function to collect the data of interest. Improvements and modifications will make the system more robust and user-friendly, as well as making it possible to address additional research questions. Incorporating solar panels will improve battery life, allowing the system to remain in the field for more extended lengths of time. The main focus is on integrating solar panels that will trickle charge both the 12 volt sensor battery and the D cell batteries that power the MICA2 and MDA300 boards. Solar converters will be connected to sealed lead acid batteries which can be trickle charged to 6-8 volts and then stepped up to 12 volts and stepped down to 3 volts, as needed for the various components. This has undergone preliminary testing and will be subjected to more extensive field tests during a deployment in the spring. In addition, solar panels will also provide a way of measuring ambient light striking the surface of each pod. This will provide a valuable comparison to the submersible light sensors which are currently being developed and modified from the design of Tatina (1998) in order to quantify subsurface light intensities. Collaborations are also under way to develop a range of custom-built sensors, enabling a broader range of chemical and microbiological parameters to be measured. Developing such sensors in house will also ultimately decrease the cost of the LakeNet system.

The long-term goals of LakeNet are to build and deploy a relatively inexpensive network of sensors in lakes and wetlands that can collect data *in situ* for extended periods of time. Wireless data transmission to relay stations and an embedded PC gateway will facilitate remote interactions, and in-network computation to detect change points in the data stream will trigger altered sampling strategy in response to sensed events. The use of an ‘intelligent’ network will increase sensor shelf life, allow for calibration and accuracy checks, and permit real-time control. Such a network will make it possible to study diurnal fluctuations in various hydrological and biogeochemical parameters related to the degradation of dissolved organic matter, interactions between ground and surface water, algal blooms, and other areas of interest. Ultimately, it will be part of a ‘total water quality’ network that monitors water from source reservoirs through a city and all the way to treatment plants and beyond.

Conclusions

The successful development and test-deployment of LakeNet provided detailed data on diurnal fluctuations in pH, temperature, and dissolved oxygen concentrations that were consistent with photosynthetic reactions in the photic zome of a small eutrophic lake. This preliminary research demonstrated the likely benefits of testing any novel sensor network in a convenient location before field deployment at a remote site. In a real sense, the research on environmental sensor networks is just beginning, with many exciting challenges that will require interdisciplinary collaboration.

As environmental sensor networks become more widespread, it is imperative for the scientific and engineering communities to be aware of the potential for the networks themselves to become ‘pollution’ and to focus on environmentally friendly network design, including removal/retrieval plans and strategies. Finally, it will be crucial to integrate new sensor network methods with existing strengths such as the programs at the U.S. Geological Survey, the NOAA National Weather Service, and the National Science Foundation’s Long-Term Ecological Research (LTER) centers, as well as incorporating new initiatives involving integrated observatories for hydrological, ecological, and related sciences.

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Figure Captions

Figure 1. The internal components of each sensor pod include A) 2 D cell batteries to power the MICA2/MDA300, B) a 12 volt battery to power the three sensors, C) wires from the probes, D) MICA2/MDA300 boards, E) the MICA2 antenna, and F) the sensor interface board.

Figure 2a. A pod with the three sensor probes as it is being deployed. From left to right are the dissolved oxygen and temperature probes hanging from the pod and the pH probe in the hand of the student.

Figure 2b. A completed pod with a polyethylene ring for stability and added buoyancy. The antenna and sensor wires are also visible.

Figure 3. A schematic showing the wireless communication network between the pods and the gateway, as well as between neighboring pods.

Figure 4. The location of St. Mary's Lake on the western side of the University of Notre Dame campus. The placement of the eight LakeNet sensor pods is also shown schematically.

Figure 5. Photograph of the eight LakeNet pods deployed in St. Mary's Lake.

Figure 6. Daily air temperatures ranged between -2 and 21^{o}C during the deployment with the average high at 16^{o}C and the average low 4^{o}C. (source: www.weather.com for zip code 46556)

Figure 7. Data collected by one of the temperature probes on one of the LakeNet pods during the Fall 2005 deployment. Dates are labeled such that x-axis ‘ticks’ correspond to the 4:30 PM sampling time.

Figure 8. Data collected by one of the pH probes on one of the LakeNet pods during deployment. Dates are labeled such that x-axis ‘ticks’ correspond to the 4:30 PM sampling time.

Figure 9. Data collected by one of the dissolved oxygen probes on one of the LakeNet pods. Dates are labeled such that x-axis ‘ticks’ correspond to the 4:30 PM sampling time.

Table 1. Major element concentrations near the LakeNet deployment site.

Element	*Concentration (ppm)*
Al	<0.090 *
Ca	53.05
Fe	<0.082 *
K	2.98
Mg	20.23
Na	50.68
P	0.18
S	23.15
Si	0.81

Other Parameters	
Water Temperature (°C)	8.6
pH	8.01
Conductivity (µS/cm)	785
Dissolved Organic Carbon (ppm)	3.43

Samples collected 14-November, 2004.

*Detection limit reported because measured values below detection.

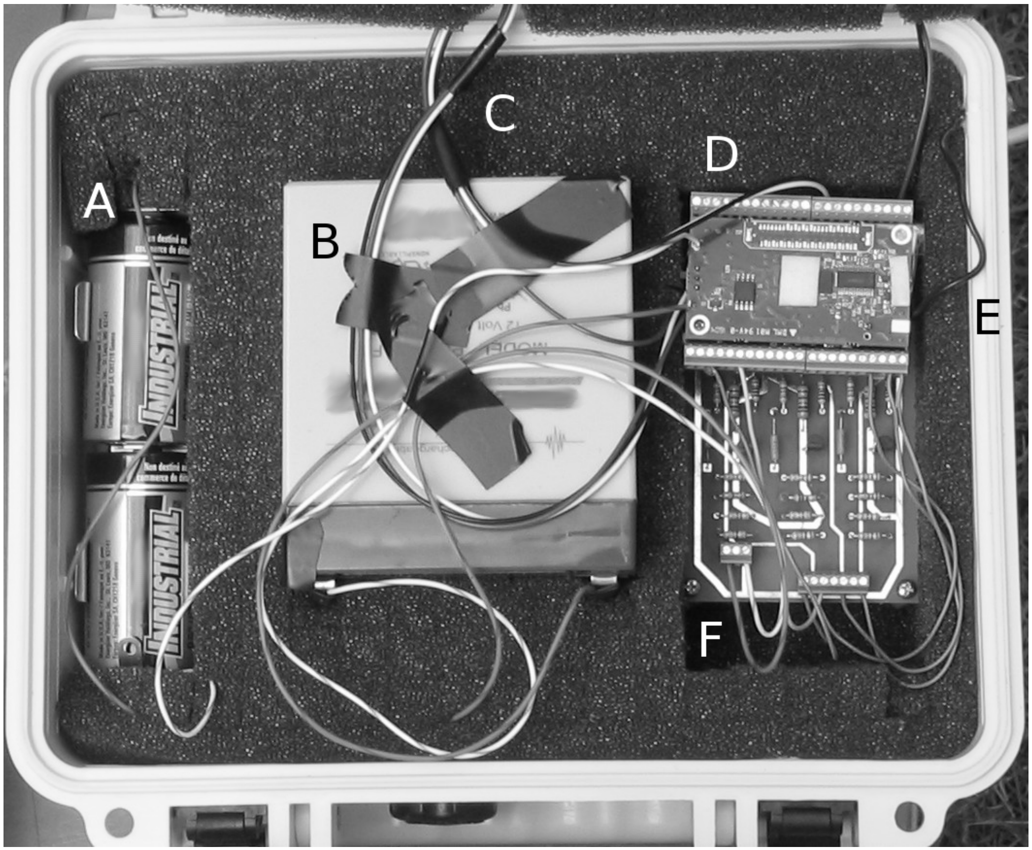


Figure 1.

Figure 2a.

Figure 2b.

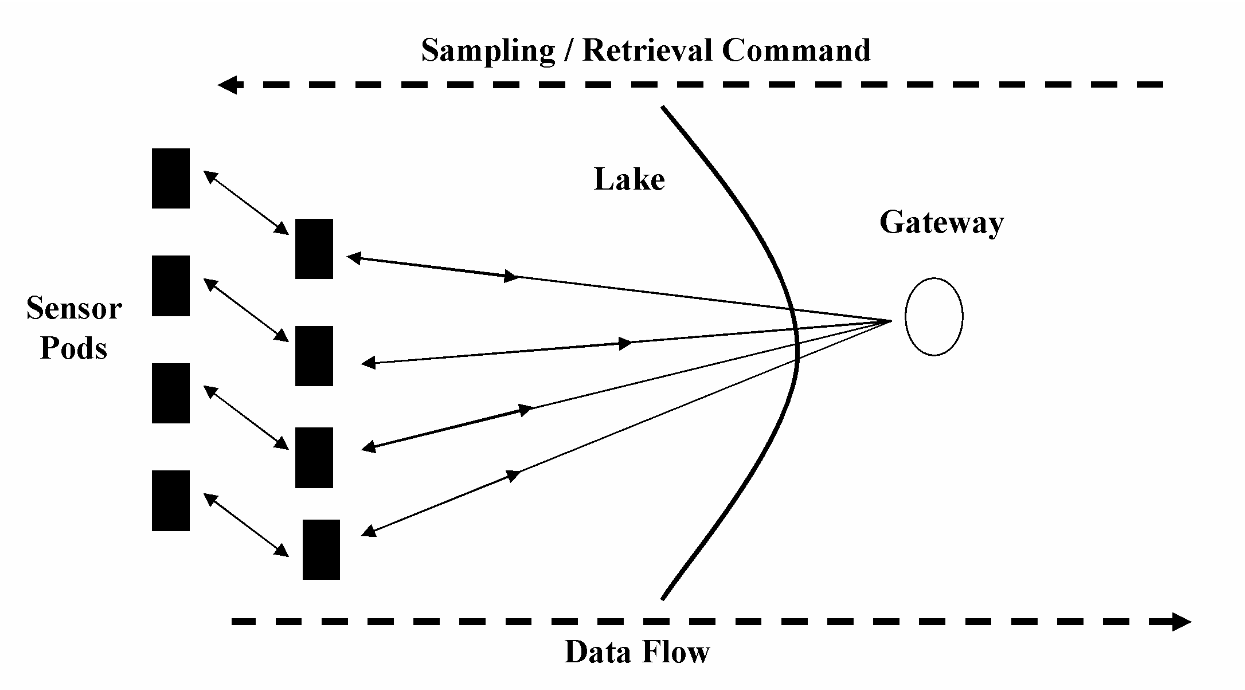

Sampling / Retrieval Command
Lake
Gateway
Sensor Pods
Data Flow

Figure 3.

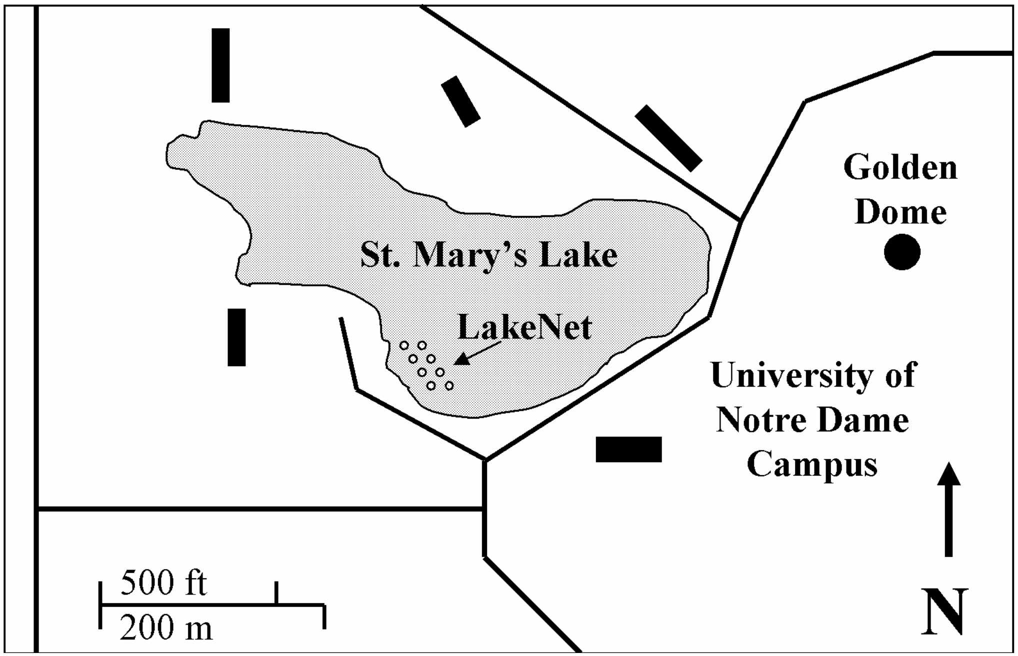
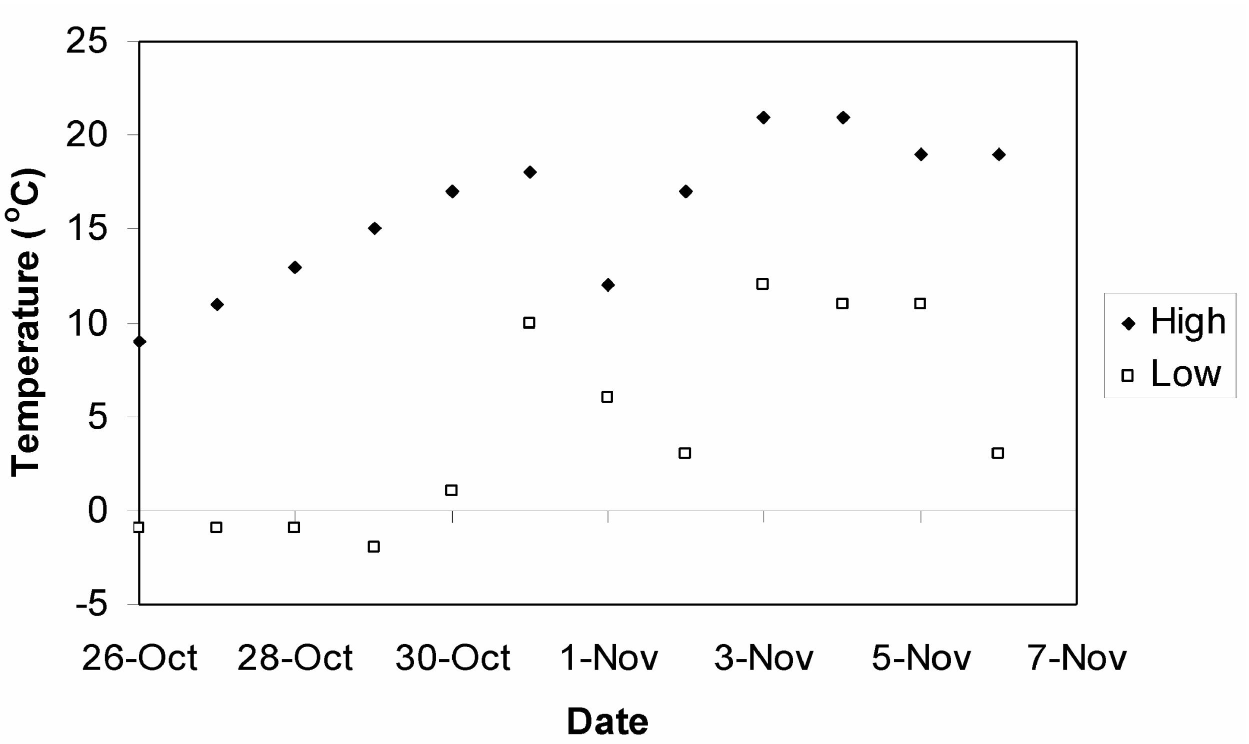

Golden
Dome
St. Mary's Lake
LakeNet
University of
Notre Dame
Campus
500 ft
200 m
N

Figure 4.

Figure 5.



25
20
15
10
5
0
-5
Temperature (°C)
26-Oct
28-Oct
30-Oct
1-Nov
3-Nov
5-Nov
7-Nov
Date
◆ High
□ Low

Figure 6.

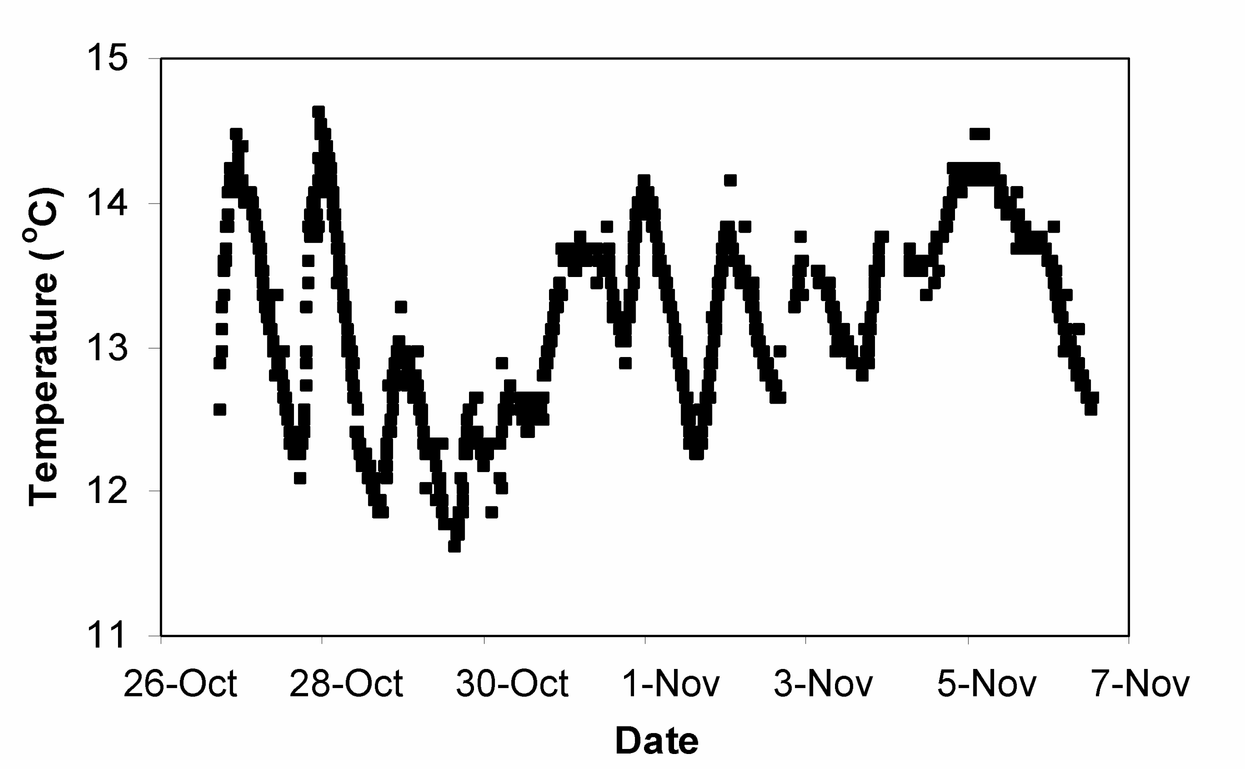

15
14
13
12
11
Temperature (°C)
26-Oct
28-Oct
30-Oct
1-Nov
3-Nov
5-Nov
7-Nov
Date

Figure 7.

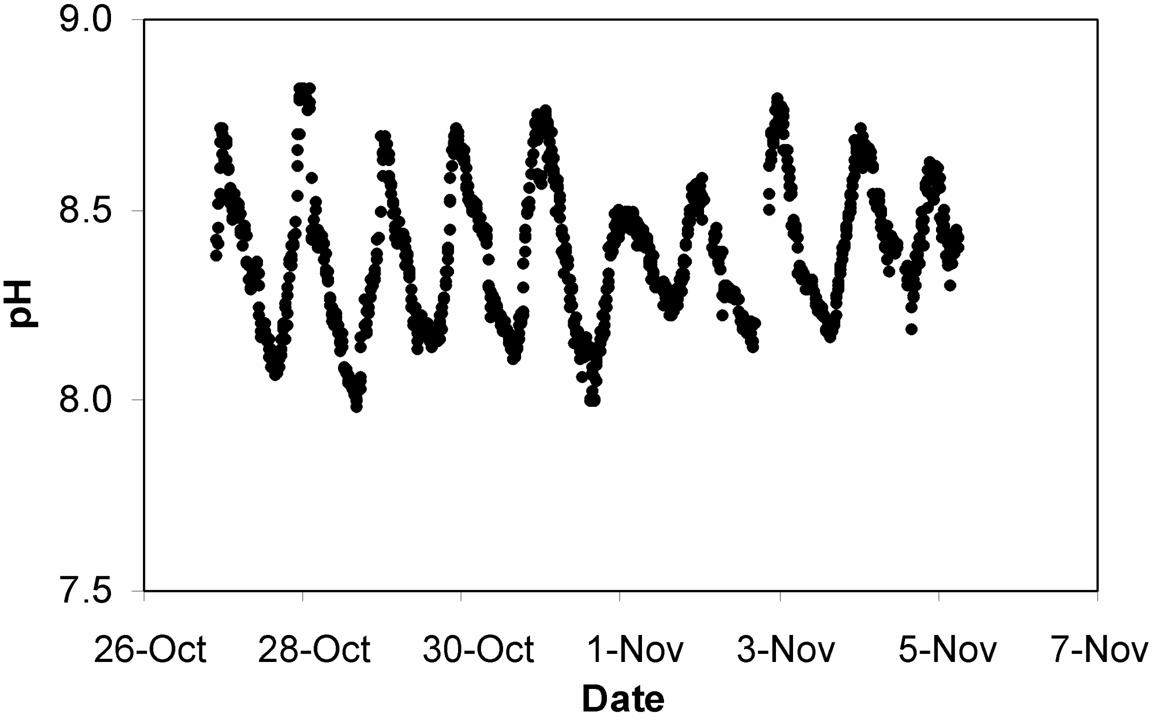


Figure 8.

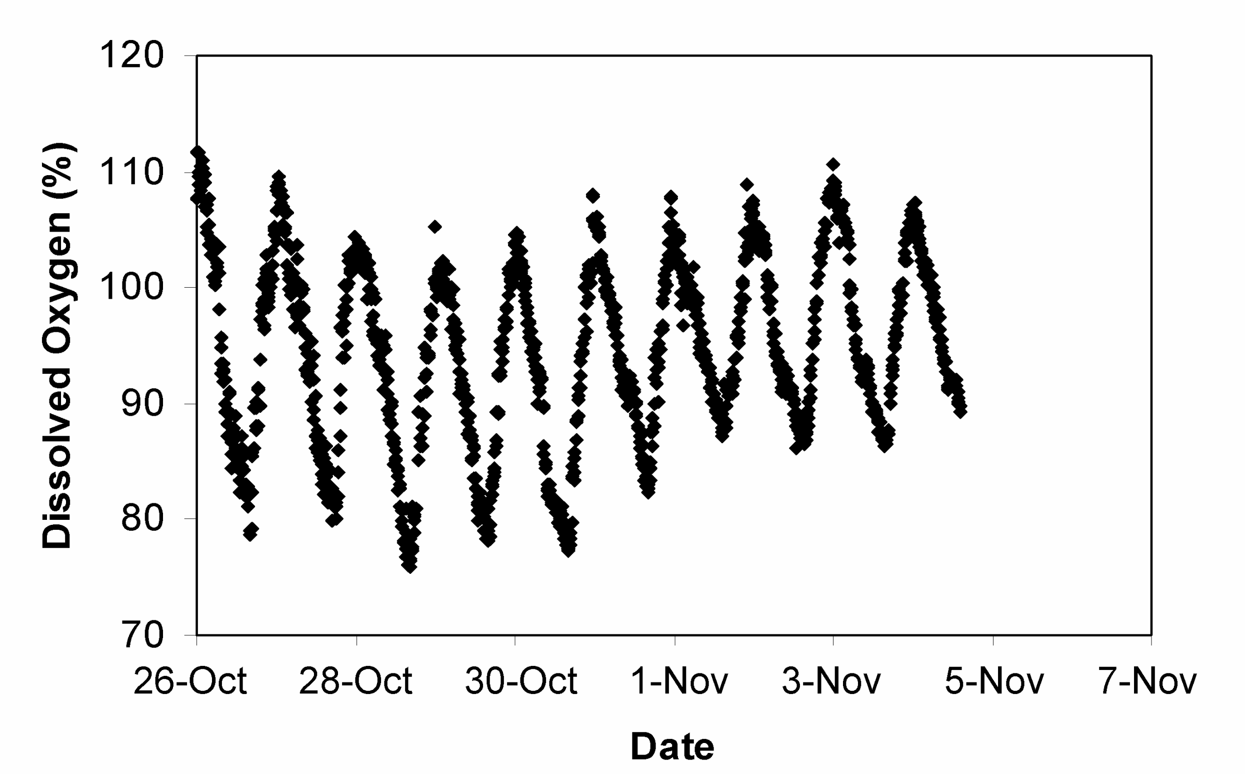

120
110
100
90
80
70
Dissolved Oxygen (%)
26-Oct
28-Oct
30-Oct
1-Nov
3-Nov
5-Nov
7-Nov
Date

Figure 9.