Public Service Commission of Wisconsin
& The Statewide Energy Efficiency and Renewables Administration

Environmental and Economic Research and Development Program

Final Report

August 2008

Monitoring the Impact of Climate Change on Water Resources in the Northern Highland American Legion State Forest in Wisconsin (NHAL)

Prepared by:
Carl J. Watras, PhD
Wisconsin Department of Natural Resources

This report in whole is the property of the State of Wisconsin, Public Service Commission of Wisconsin, and was funded through the FOCUS ON ENERGY program.

focus on energy℠
The power is within you.

Executive Summary

Situated within the northern highland lake district of Vilas and Oneida counties, Wisconsin's NHAL State Forest contains more than 900 lakes and 126 streams - the largest group of undeveloped waters in Wisconsin. While many water resources in Wisconsin are threatened by over-development, the water resources of the NHAL may be threatened more by climatic changes associated with greenhouse gas emissions and global warming. Changing climatic patterns are expected to result in more frequent heavy precipitation events (and consequent flooding) as well as higher rates of evaporation due to warmer temperatures and shorter periods of ice-cover. Although the net impact of these opposing forces is uncertain, the exchange of water and solutes between lakes, their terrestrial watersheds, and the atmosphere may change in ways that have profound biogeochemical and ecological implications.

The purpose of this project was to develop a reliable, low-cost method to quantify and track these potential climatic impacts. We proposed to evaluate various remote sensing technologies, and then deploy a prototype network of remote sensors within a typical NHAL catchment. The remote sensors would monitor hydrochemical gradients between a small lake, a surrounding wetland and the atmosphere. The prototype network would serve as a model for monitoring efforts across a wide variety of NHAL catchments.

Based on information from remote sensing experts, we elected to develop a wireless platform based on CrossBow's™ low-power "mote" technology. The CrossBow mote consists of a miniature microprocessor and radio (smaller than a deck of cards) that can

be connected directly to sensors that are embedded in the field. When programmed appropriately, motes can run unattended for months on a few AA batteries. A cluster of motes deployed within a watershed could theoretically form a network that sends data back to a distant base station in near-real time via a single high power radio. In our prototype application, we proposed to interface the mote network with an existing high-power radio network operated by the University of Wisconsin (www.gleon.org). This “piggyback” approach would minimize costs, conserve power and allow broad dissemination of data via the Internet.

In collaboration with colleagues at UW-Madison, we designed a sensor network that could relay field data from the Crystal Bog catchment back to the UW-Trout Lake Station via the GLEON radio transmitter. An undergraduate student in the Department of Electrical and Computer Engineering built the sensor nodes and programmed the motes. Nodes were designed to record and transmit data on rainfall, lake water and groundwater at three minute intervals. A research specialist at the Center for Limnology facilitated the GLEON interface that coordinated the long distance flow of data.

The network was deployed in the CB catchment at the end of summer 2007, and we began field testing. There were four sensor nodes in the prototype network. One node monitored precipitation; one node monitored lake-water; and two nodes monitored ground-water in the surrounding wetland. The deployment was successful and preliminary results were promising, but not flawless. Power consumption was higher than expected, and data from the lake and wetland nodes frequently had erroneous values.

Further evaluation indicated that subtle hardware malfunctions and software bugs were causing the problems. To resolve these issues, a second one year proposal was submitted to FOE in May 2008. A second phase of the project was initiated in July 2008, with support from FOE.

Study Site.

The Northern Highland Lake District (NHLD) of Wisconsin contains thousands of kettle lakes that were formed during the last period of continental glaciation. It is a hummocky region of pitted outwash with low topographic relief (~40m) that spans several river basins, including headwaters of the Wisconsin, Chippewa (Mississippi) and Presque Isle rivers (Superior). The region is sparsely populated, covered with mixed hardwood/coniferous forest and underlain by 30 to 60 m-thick deposits of glacial drift (Attig, 1985). Due to the low relief and variable drift composition, wetlands are abundant. Despite several streams, surface flow is poorly integrated because the lakes are situated in a landscape and soil matrix that is more conducive to groundwater flow (Webster et al., 2006). About 40% of the lakes are seepage systems with no inlet or outlet.

The Trout Lake watershed is nested within the NHLD, and it has been intensively studied since 1982 as part of the NSF-LTER northern temperate lakes program (Magnuson et al., 2006). The total watershed area is 130 km^2. It comprises 115 lakes and ponds with a total surface area of 30 km^2. Wetlands constitute roughly 7% of the terrestrial surface. Across the watershed, groundwater elevations vary from about 514 m, asl to 492 m, asl, with Trout Lake being the terminal discharge point (Figure 1).

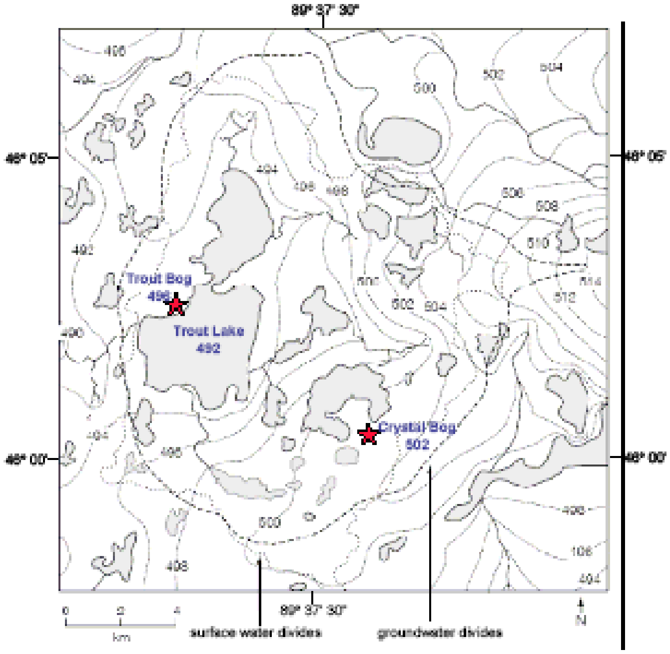

Figure 1. The Trout Lake watershed in northern Wisconsin. Stars indicate the two wetland sub-catchments in the NTL and GLEON networks

The Crystal Bog sub-catchment (CB, 46^{o}00’30” N, 89^{o}36’30” W) is situated at a relatively high elevation near the top of the Trout Lake watershed (Fig 1). It comprises a weakly minerotrophic fen (7 ha) surrounding a small bog pond (0.5 ha) that has no channelized inflow or outflow. The sub-catchment overlies deep outwash and glacial till typical of the region. The peatland surrounding the lake varies in thickness from 2m to 7m, and groundwater discharge has been estimated to constitute 3% to 17% of the catchment’s annual water budget (Kratz and Medland 1989). Direct precipitation is the dominant hydrologic input to the sub-catchment as a whole.

The CB sub-catchment is being studied intensively as part of the Global Lake Ecological Observatory Network (GLEON, www.gleon.org), sponsored by an international consortium of funding agencies, including the US National Science Foundation. Each individual observatory consists of a small buoy equipped with sensors that continuously monitor key limnological variables, such as water temperature and dissolved oxygen concentration, as well as meteorological variables that affect water motion and heating (e.g. wind speed, wind direction, air temperature, sunlight). Data from the sensors on the buoys are relayed in near-real time via radio-telemetry to a computer base-station at the Trout Lake Laboratory, where web-accessible databases are maintained (Figure 2).

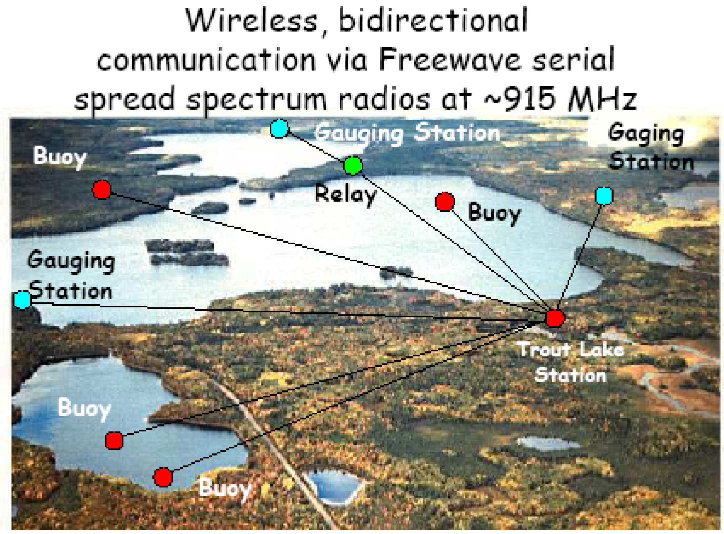

Figure 2. GLEON remote sensing buoys currently located on lakes and streams in the NHAL (UW-Madison Trout Lake station). This system relays data from sensors on buoys in 4 NHAL lakes and 3 stream gauging stations back to TLS via radio-telemetry. The data can be viewed in real-time at the lab and via the lab website. The buoys are part of the Global Lake Ecological Observatory Network (GLEON). It is operated by the UW-Madison Center for Limnology in conjunction with the NSF-sponsored North Temperate Lakes Long Term Ecological Research project (NSF NTL-LTER). Our wireless network in the CB catchment piggy-backs on GLEON.

Since the GLEON buoy on CB does not monitor lake level, rainfall or wetland groundwater, changes in the hydrological status of the sub-catchment are undocumented. However, a classical study of the hydrology of Crystal Bog was conducted in 1985 by Marin et al (1990). In that study, a network of monitoring wells was established in the wetland surrounding the bog pond. Water levels in the wells and in the bog pond were manually recorded bi-weekly between May and November, 1985. Samples for water chemistry were collected 5 times during this period. The direction of water flow and the exchange of solutes within the catchment were inferred from these data.

Marin et al. (1990) reported that there were seasonal shifts in the flow regime between the pond and the wetland (Figure 3). During June, water in the bog pond tended to flow into the wetland, changing the chemistry of wetland porewaters. But during August, this flow was reversed and water tended to flow into the pond from the wetland, changing the chemistry of the pond. There was also limited evidence that the exchange of water and solutes between the pond and the wetland was affected by individual precipitation events. However, the frequency of manual data collection was not sufficient to detect changes over such short time-scales, so that result was considered speculative. Nevertheless, Marin et al (1990) conclusively showed that water quality in the pond and in the wetland depended on the direction of flow, and that the direction of flow was related to hydrologic conditions that changed on at least a seasonal time-scale. Their observations might also explain why the CB lake water is relatively dilute when compared to other bog lakes in the region.

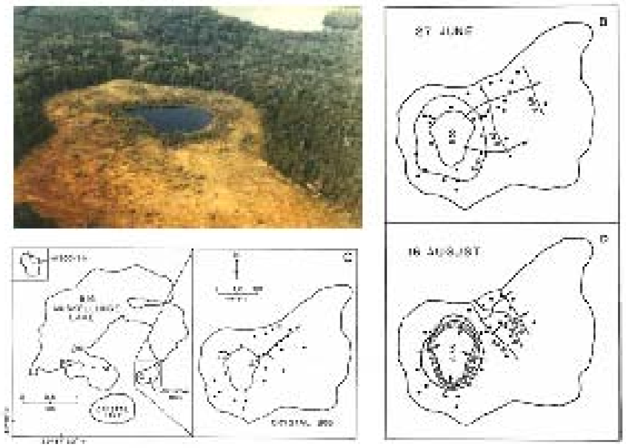

Fig 3. Crystal Bog sub-catchment and results of manual monitoring by Marin et al (1990).

Study Objectives.

The primary objective of this project was to design, construct and deploy an automated monitoring network that could track hydrologic changes in the CB catchment over a multi-year time scale. It would serve as a model for monitoring catchments across the NHAL and Wisconsin as a whole. The network would continuously track water levels and bulk solute concentrations at diverse locations in the catchment using high-precision sensors. The sensors (water level and conductivity) would be deployed in the wetland to monitor near-surface ground water and in the lake itself. Precipitation would be monitored on-site at the same time-scale as water level and conductivity (i.e. 15 minute intervals). The proposed network would be designed so that data could be relayed back to the UW Trout Lake Station in near-real time by "piggy-backing" on the GLEON buoy. Signals from the hydrochemical sensors would be transmitted to the long-range radio on the buoy, and from there they would be relayed to the TLS and the Internet.

The main performance criteria for each sensor node in the network were:

1. Low power consumption,
2. High reliability,
3. High data validity,
4. Bi-directional communication with the base station and the Internet.

Cost was also an important criterion, and our goal was a cost per node of less than $1500.

The prototype network would provide a tool for documenting the hydrologic response to climate change. Climate models for the upper Midwest indicate that our weather will gradually become warmer and wetter as a result of green house gas emissions, with the average annual temperature increasing by about 4° F over coming decades. This projection doesn’t mean that daily temperatures would rise uniformly by 4° F. Instead, summer heat waves would be longer and hotter, and nighttime winter temperatures wouldn’t sink so low. Precipitation could increase by as much as 10% on average, but much of the increased precipitation could come in the form of intense storms, leading to local flooding and more runoff. Seasonal precipitation patterns could also change, with more rain coming in the winter and less in the summer. Less rain in the summer, paired with increased evaporation caused by warmer temperatures, could trigger more severe summer droughts.

All these climatic changes have broad implications for the water resources of Wisconsin. Warmer water temperatures may lead directly to increased eutrophication of lakes and streams (due to higher algal growth rates at higher temperatures) as well as loss of habit for cold water fishes and invertebrates. In addition, changes in precipitation patterns and evaporation rates may have equally profound indirect effects by altering the exchange of water within individual catchments. This exchange governs the flux of nutrients and other solutes between lakes, their terrestrial watersheds and the atmosphere. These hydrochemical fluxes in turn govern the ecological character and biodiversity of our surface waters. In our project, the focus was on developing an infrastructure to document these subtle indirect effects of climate change.

Project Results.

The prototype network with four nodes is shown on Figure 4. The network comprises: 1) a weather node, to monitor precipitation on site; 2) a lake node, to monitor water level in the lake along with conductivity and temperature; 3) a wetland node, to monitor water level in the wetland along with conductivity and temperature; and 4) a gateway node, to integrate the sensor mesh with the GLEON communication system sending data back to the laboratory at Trout Lake Station (TLS). In late summer 2007, the four nodes transmitted data back to TLS at pre-set intervals of about 3 minutes. The data were viewable graphically at TLS in near-real time, and they could also be viewed in Madison via the internet.

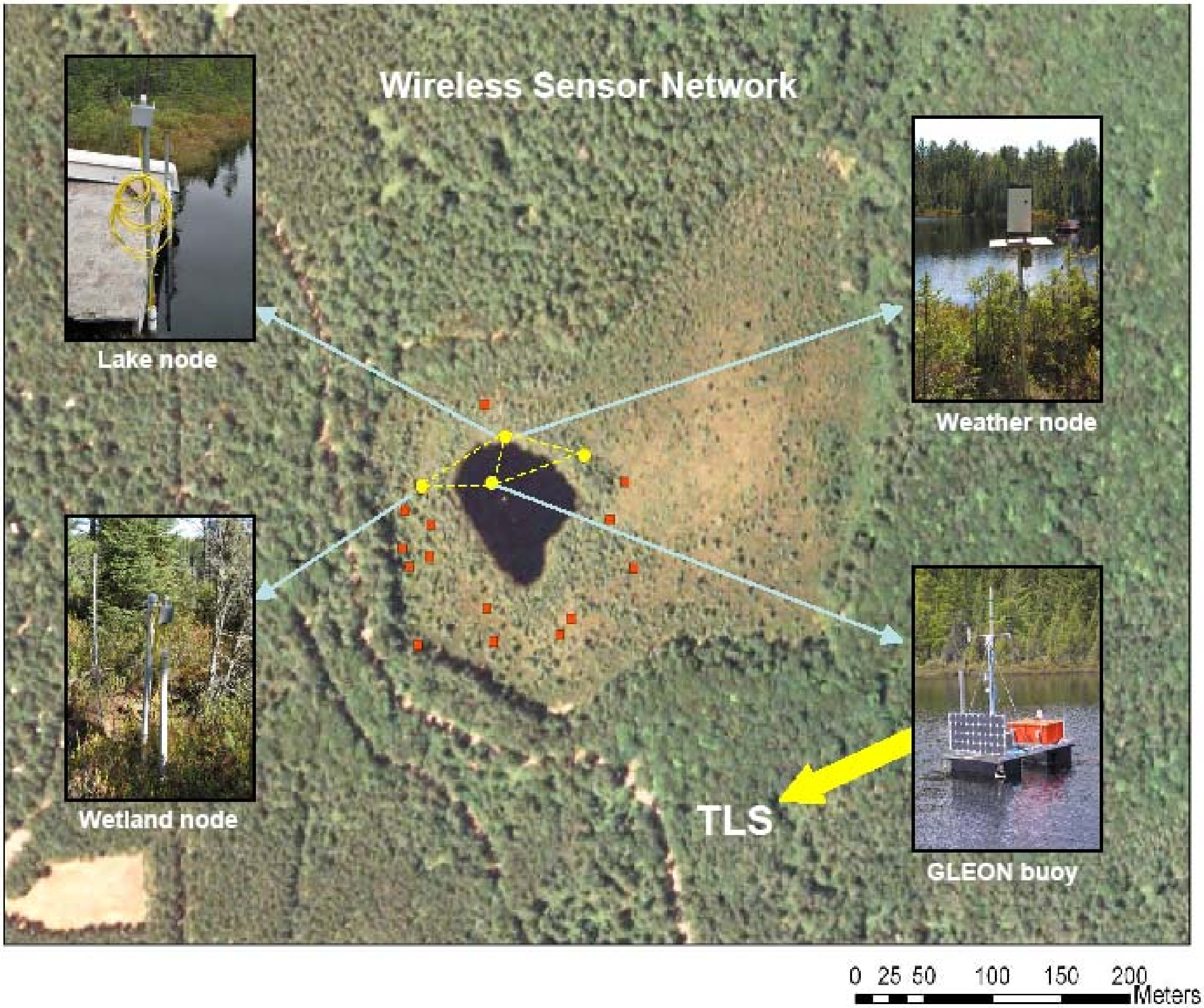

Fig. 4. Prototype wireless sensor network in Crystal Bog subcatchment, 2007. Wireless nodes are yellow. Red squares indicate manual monitoring wells of Marin et al (1990).

The heart of each embedded sensor node consisted of a data acquisition board, a microprocessor chip and a low-power radio transmitter/receiver. This package was smaller than a deck of cards; and, complete with battery pack, it fit into a standard electrical outlet box (Fig 5). The outlet box served as a weather-proof housing that could be mounted inconspicuously in the field. The circuitry for each node was designed and constructed by a summer student in Electrical and Computer Engineering at UW-Madison (Sean Scannell) under the supervision of Professor Yu Hen Hu.

The sensors for water level, water conductivity and water temperature were purchased from commercial vendors and wired into the mote by the summer student. This task involved constructing a circuit board that directed battery power to the sensors and directed data from the sensors to the microprocessor/radio.

After each node was constructed, the mote was programmed to turn the sensors and radio on and off in a power-conserving “sleep” cycle. Our objective was to keep the unit “sleeping” for most of the time and, thereby, conserve battery power. For our prototype, the nodes were programmed to activate the sensors for a 3 second warm-up period, collect data, transmit data and then go back to sleep. The duty cycle was set at 3 minutes, so that the node was theoretically sleeping more than 90% of the time. Battery voltages were monitored continuously, al

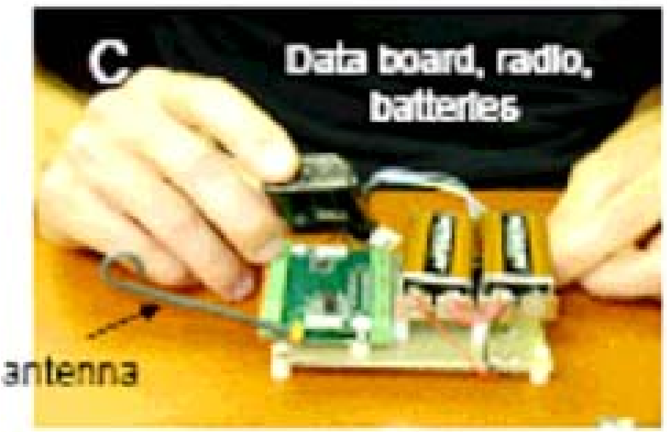

Fig. 5. Prototype mote assembly showing sensor interface boards, microprocessor, radio and battery pack. Unit is later attached to sensors and housed in weather-proof box for field deployment. Designed and constructed by Sean Scannell, ECE, UW-Madison

The data record for a two-week period of field deployment is shown on Figure 5. The data indicate a rapid response to a rainfall event in the wetland but not in the lake. The lake data also show an unexplained spike during day 5.

The rainfall node performed well for more than one month without a significant voltage change in the two AA batteries. Onset of winter prevented a full evaluation of this node, but overall performance was highly promising. For the lake and wetland nodes, rates of power consumption were too high for extended field deployment. We attempted to remedy this problem by re-programming the nodes; and although a modest increase in power efficiency was achieved, there was a dramatic decrease in the reliability of data. Further trouble-shooting identified an intrinsic fault in the data acquisition board as well as voltage bleeds in some components on the sensor interface board. We were not able to fully resolve these problems within the project time period.

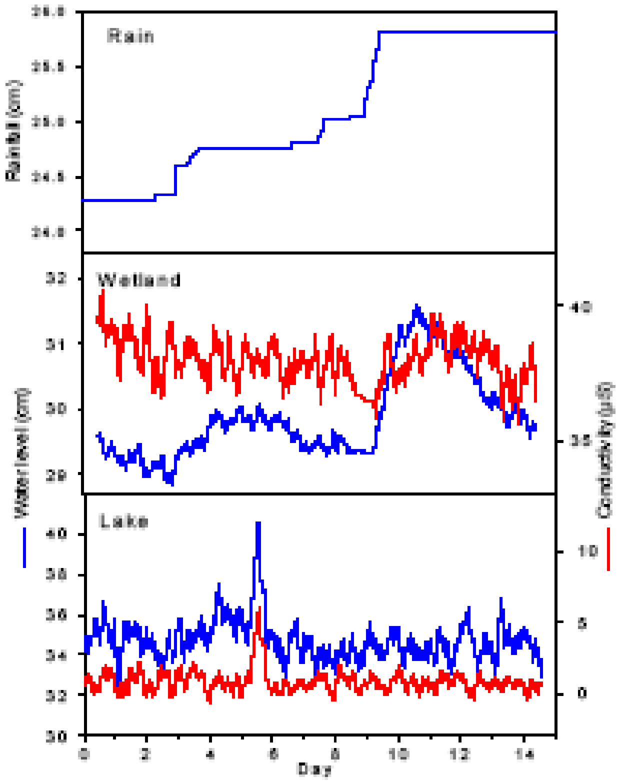

Fig. 6. Data from prototype network in CB showing response of wetland porewaters and lake water to precipitation events for 2 weeks in November 2007. Water levels not yet referenced to a common datum or QA/QC assured (collection interval ~ 3 min.)

Because many of the results were promising, we applied to FOE for continued support in a Phase II project that began on July 1, 2008. The primary objectives of Phase II are to resolve the power consumption and data reliability problems encountered at the end of Phase I, and to expand the number of nodes in the CB wetland. We will also develop a website for broader dissemination of the data.

References.

Attig J.W. 1985. Pleistocene Geology of Vilas County, Wisconsin. Wisconsin Geologic and Natural History Survey, 50, 32p.

Kratz T.K. and Medland V.L. 1989. Relationship of landscape position and groundwater input in northern Wisconsin kettle-hole peatlands. In: Sharitz R.R. and Gibbons J.W., editors. *Freshwater Wetlands and Wildlife*. p. 1141-1151.

Magnuson J.J., Kratz T.K., Benson B.J., eds. 2006. *Long-term Dynamics of Lakes in theLlandscape*. Oxford University Press. 400 p**.**

Marin L.E., Kratz T.K., Bowser C.J. 1990. Spatial and temporal patterns in the hydrogeochemistry of a poor fen in northern Wisconsin. Biogeochemistry **11**: 63-76.

Webster, K.E., Bowser, C.J., Anderson, M.P. and Lenters, J.D. 2006. Understanding the lake-groundwater system: Just follow the water. *In* Long-Term Dynamics of Lakes in the Landscape. *Edited by* J.J. Magnuson, G.J. Kenoyer and B.J. Benson. Oxford University Press. pp. 19-48.

Acknowledgments.

This project was funded by Wisconsin's Focus on Energy program and the Wisconsin Department of Natural Resources. Construction and deployment of the mote network in CB was conducted by Ken Morrison, research scientist, WDNR, and Sean Scannell, undergraduate student, Department of Electrical and Compute Engineering, UW-Madison; with support from Yu Hen Hu, professor, Department of Electrical and Compute Engineering, UW-Madison, and Luke Winslow, Center for Limnology, UW-Madison