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& The Statewide Energy Efficiency and Renewables Administration**

## **Environmental and Economic Research and Development Program**

**Final Report**  
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### ***Monitoring the Impact of Climate Change on Water Resources in the Northern Highland American Legion State Forest in Wisconsin (NHAL)—Phase II***

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# **Monitoring the impact of climate change on water resources in the Northern Highland/American Legion (NHAL) State Forest in Wisconsin: Phase II**

## **Executive Summary**

This broad objective of this project was to design and deploy a wireless, remote sensor network that could monitor the hydrochemical impact of greenhouse gas emissions and global warming on remote lakes and wetlands within the Northern Highland American Legion State Forest (NHAL) of Vilas and Oneida counties. With over 900 lakes and 120 streams, the NHAL contains the largest group of undeveloped and nearly pristine waters in Wisconsin. Predicted changes in Wisconsin's climate have several implications for these valuable water resources. More intense summer storms and longer periods of evaporation are expected to alter water budgets and impact the exchange of solutes with terrestrial watersheds. These changes may have profound biogeochemical and ecological implications.

The design envisioned integrated sensor nodes to monitor water levels, water chemistry, rainfall and evaporation in a small subcatchment of the Trout Lake watershed. Our goal was an automated array of sensors that could function semi-autonomously for months at a time and allow data display in near-real time at a distant base station. Low power consumption, low cost, high precision, high accuracy and high reliability were our main performance criteria. After successful deployment, the prototype sensor network would then serve as a model for additional monitoring efforts across a wider variety of NHAL catchments.

This report summarizes the results of Phase II of a multi-year effort. During Phase I, we evaluated several remote sensing technologies, and then we deployed a prototype network of radio-controlled sensors within a wetland-dominated NHAL subcatchment. The hardware platform for PI (the first prototype) was the MICA2 mote from CrossBow Technology, Inc of Milpitas, CA. The CrossBow<sup>®</sup> mote consists of a miniature microprocessor and radio that can be connected to sensors embedded at the field site. When deployed, the motes form a self-healing, mesh network that can compensate for certain environmental interferences. We interfaced the PI mote network with an existing high-power radio network operated by the University of Wisconsin ([www.gleon.org](http://www.gleon.org)). This "piggy-back" approach minimized costs, conserved power and allowed the transmission of data from the catchment directly to The UW-Madison's Trout Lake research station in near-real time.

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

During this second phase (2008-09), we improved the electrical circuitry at the heart of each CrossBow node, and we re-deployed network in Crystal Bog. The result was enhanced performance: i.e. lower power consumption and higher reliability. We worked closely with Professors Yu Hen Hu and Michael Morrow, Department of Electrical and Computer Engineering, UW-Madison to make these improvements. Mr. Steven Yazicioglu, an ECE undergraduate, worked as a summer student on the project. In addition to the instrumentation that we designed and constructed, we also deployed a small array of commercial radio-sensors obtained from Instrumentation Northwest, Inc. of Kirkland, WA. Our purpose was to compare "build or buy" network options.

This report summarizes the project status as of October 1, 2009, when Phase II was completed. The technology is described in detail, and the results of field deployments in Crystal Bog and Trout Bog are presented. We also describe progress made in cooperation with a local non-profit organization to establish a citizen-based environmental monitoring network with broader coverage across Vilas County.

## **Monitoring the impact of climate change on water resources in the Northern Highland/American Legion (NHAL) state forest in Wisconsin: Phase II**

**Background and Summary.** This report summarizes the second phase of a project to monitor the impact of greenhouse gas emissions and global warming on remote lakes and wetlands within the Northern Highland American Legion State Forest (NHAL) of Vilas and Oneida counties. With over 900 lakes and 120 streams, the NHAL contains the largest group of undeveloped and nearly pristine waters in Wisconsin. Predicted changes in Wisconsin's climate have several implications for these valuable water resources. More intense summer storms and longer periods of evaporation are expected to alter water budgets and impact the exchange of solutes with terrestrial watersheds. These changes may have profound biogeochemical and ecological implications.

The objective of this project was to develop a network of remote sensors to monitor key hydrochemical variables within a small, wetland-dominated, NHAL catchment. Sensor nodes would be distributed across the catchment to monitor water levels, water chemistry, rainfall and evaporation. Our goal was an automated array of sensors that could function semi-autonomously for months at a time and allow data display in near-real time at a distant base station. Low power consumption, low cost, high precision, high accuracy and high reliability were our main performance criteria. After successful deployment, the prototype sensor network would then serve as a model for additional monitoring efforts across a wider variety of NHAL catchments.

During Phase I, we evaluated several remote sensing technologies, and then we deployed a prototype network of radio-controlled sensors within a wetland-dominated NHAL subcatchment. The hardware platform for PI (the first prototype) was the MICA2 mote from CrossBow Technology, Inc of Milpitas, CA. The CrossBow<sup>®</sup> mote consists of a miniature microprocessor and radio that can be connected to sensors embedded at the field site. We interfaced the PI mote network with an existing high-power radio network operated by the University of Wisconsin ([www.gleon.org](http://www.gleon.org)). This "piggy-back" approach minimized costs, conserved power and allowed the transmission of data from the catchment directly to The UW-Madison's Trout Lake research station in near-real time.

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This report summarizes the status of the remote hydrochemical sensing network as of October 1, 2009, when Phase II was completed.

## Technology overview:

Our first generation of remote sensing nodes was constructed in-house with assistance from the UW-Madison Department of Electrical and Computer Engineering. The data-acquisition and radio communication hardware was based on the MDA300 data acquisition board (DAQ board) and the MICA2 mote from Crossbow Technology (Figs 1 & 2). These devices, called motes, accept data from sensors in the field and transmit it via radio frequency (RF) to a server for near-real time viewing.



Figure 1: MICA2 radio



Figure 2: MDA300 DAQ board

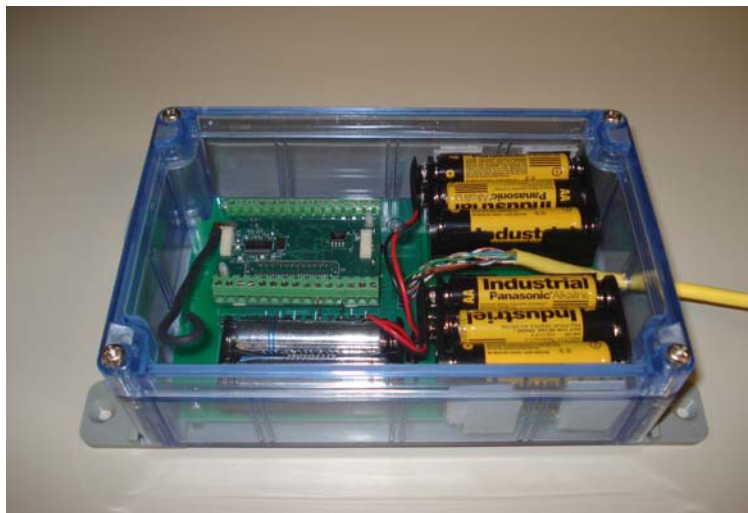


Figure 3: Wireless sensor node

There are five main electrical components in each node of the wireless network: the MICA2 mote, the MDA300 DAQ board, the mainboard PCB, the AA battery packs and the sensors (Fig. 3).

The MICA2 mote is the hardware used to transmit the acquired data via a wireless connection to the base station and to run the sensor data acquisition firmware. The components on the MICA2 include the CC1000 radio chip, which is used to transmit and receive data packets, the Atmega128L, the microcontroller which simultaneously runs the data acquisition and the network communication firmware, flash memory for the firmware and data buffers, and the antenna among other things. Nodes in this project broadcast over the 903MHz channel, although this can be changed to whichever

frequency contains the least amount of traffic at a specific site.

The MDA300 DAQ board is used mainly as an interface for the MICA2 to the rest of the system. Both the MICA2 and the MDA300 have 51-pin connectors which facilitate this connection. The MDA300 contains the I/O pins that are used to collect data from the sensors and also to control them. Also contained within the MDA300 are the analog-to-digital converters. These converters allow the microcontroller on the MICA2 to work with voltage data coming from the sensors.

The mainboard PCB contains the circuitry to control the sensors and allows for all the components within the node to connect to one another (Fig.4).

The sensors consist of most any device that varies its resistivity or current output when supplied power and put in different environmental settings. Resistors are used to scale the voltage, which is ultimately what will be transmitted by the MICA2 to the gateway, to whatever range is required. The MICA2 and MDA300 are configured to be able to handle a signal anywhere from 0V to 2.5V.

#### **Mainboard:**

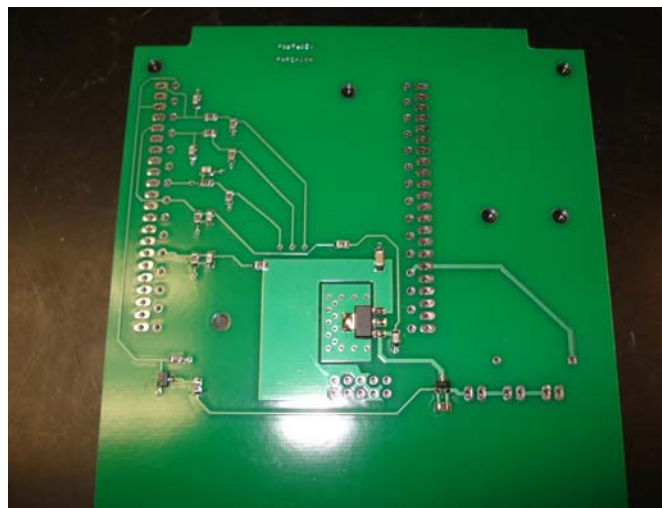


Figure 4: Mainboard PCB

The mainboard has four main functions: controlling power to the sensors, scaling and converting the sensor output, filtering the sensor output, and physically connecting this hardware to the MDA300 DAQ board. The sensors first get powered by the board, then this output gets converted to a voltage if necessary and scaled down to a voltage that the MDA300 can handle. The signal then gets filtered and finally is passed to an ADC pin on the MDA300.

*Sensor Power Control:*

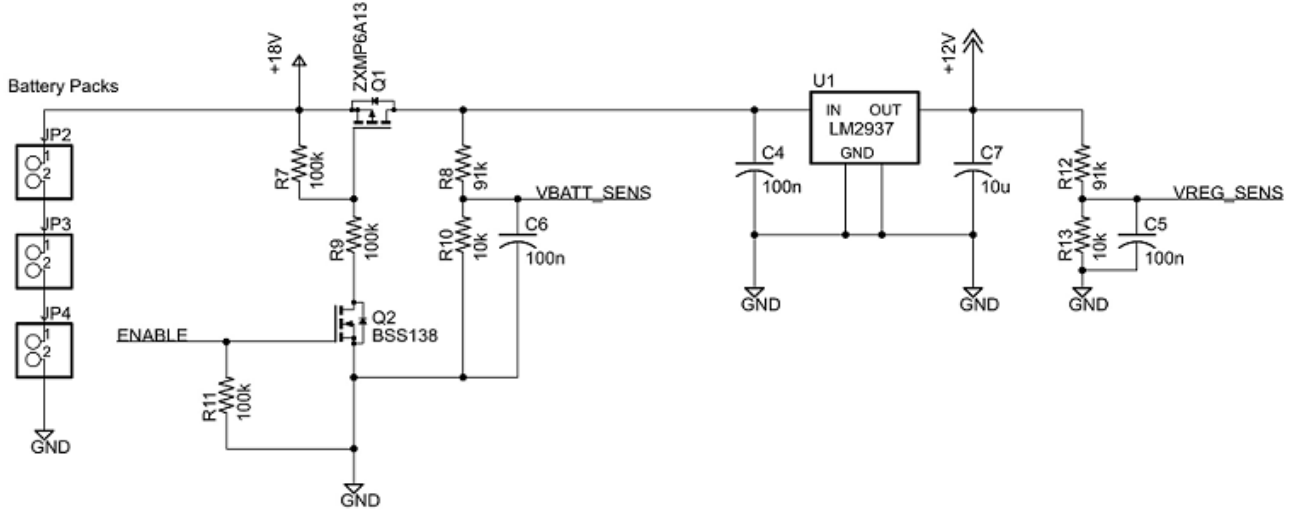


Figure 5: Sensor power control

- Q1: P-channel MOSFET
- Q2: N-channel MOSFET
- U1: 12V voltage regulator
- R8, R10: Scaling resistors for sensor battery pack monitoring
- R12, R13: Scaling resistors to monitor 12V regulator voltage

Battery packs JP2, JP3, and JP4 supply the 18V power source which is used to power the sensors. The ENABLE is connected to the E3.3 pin on the MDA300. This pin supplies a 3.3V signal when the sensors need to be turned on. When ENABLE goes high, current is allowed to pass through Q2 drain to source. This creates a positive voltage at Q1. 18V is then applied to the input of U1. This 18V gets scaled down to 1/10<sup>th</sup> its original value through R8 and R10 to be connected to the MDA300 through VBATT\_SENS so that it can be remotely monitored. U1 creates a stable 12V at its output, which is used to power the sensors. It is also scaled down to 1/10<sup>th</sup> its original value by R12 and R13 to be monitored through VREG\_SENS.

*Scaling and Converting Hardware:*

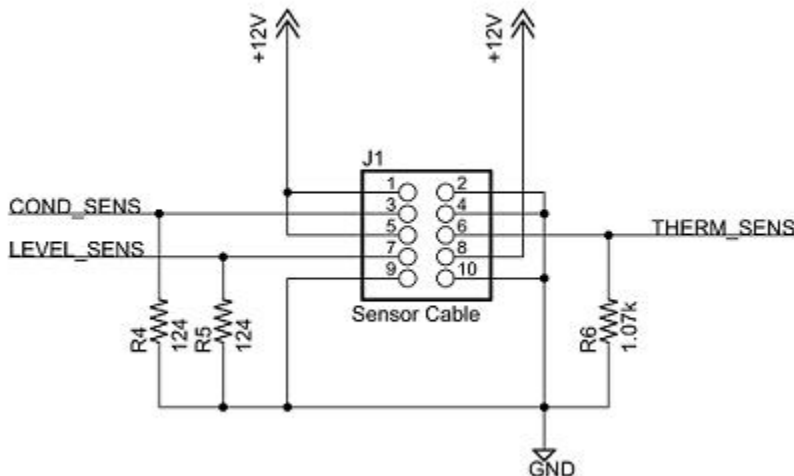


Figure 6: Sensor output scaling

- R5: Scaling resistor for ADC0
- R4: Scaling resistor for ADC1
- R6: Scaling resistor for ADC2
- J1: Jumper connection to sensors

The resistors in this diagram are the scaling resistors for the sensor output and also convert the sensor output to voltage for current-output sensors. How to decide what resistors to use here will be discussed more in the **Sensors** section of this document. The J1 header is also illustrated here. 3 pins are used as inputs to the MDA300, 3 pins are used to supply a 12V excitation to the sensors, and 4 pins are used as a ground.

*Filtering Hardware:*

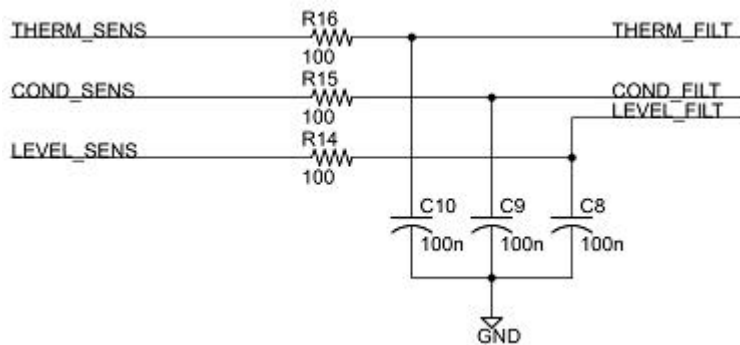


Figure 7: Filtering hardware

The filters implemented here are simple low-pass filters. Any AC noise that gets added onto the DC sensor output will be sent to ground, while the DC signal is allowed to pass to the MDA300.

*MDA300 Connections:*



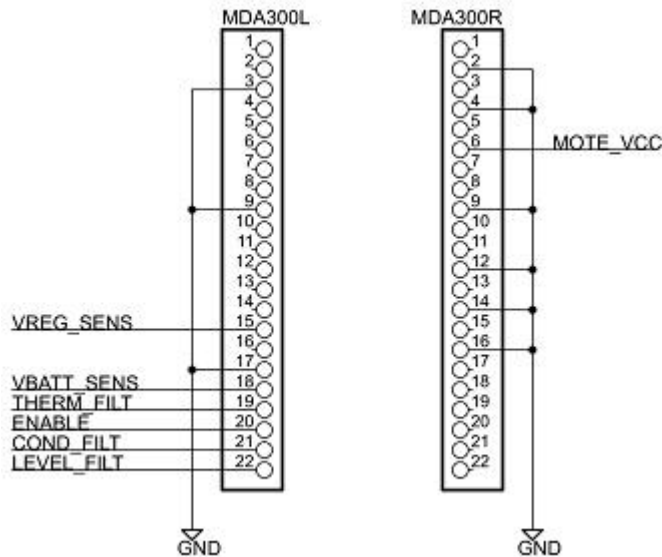


Figure 8: MDA300 pin connections

GND: Ground

MOTE\_VCC: 3V mote power

VREG\_SENS: 12V regulator voltage scaled by  $1/10^{\text{th}}$ , ADC4

VBATT\_SENS: Sensor battery pack voltage scaled by  $1/10^{\text{th}}$ , ADC3

THERM\_FILT: ADC2 input for thermistor, ADC2

COND\_FILT: ADC1 input for conductivity sensor, ADC1

LEVEL\_FILT: ADC0 input for level sensor, ADC0

Holes exist in the mainboard where nylon bolts can be inserted to provide spacing and mounting points for the MDA300. After the MDA300 is mounted on, wires need to be soldered into the correct pins on the mainboard and then inserted into the corresponding slots on the MDA300, as shown in figure 8.

### Sensors:

Several different types of sensors can be used with this mainboard setup. As stated in the **Mainboard** section, resistors exist on the board to convert and scale the sensor outputs. This configuration allows for sensors with resistive or current-based sensors to be used. Sensors must also be able to be powered by a 12V power supply.

The MDA300 ADC inputs allow for a 0 – 2.5V input range. Therefore, the correct resistors must be chosen to scale the sensor output to this range. Figure 4 shows the circuit used to scale the sensor outputs.

#### *Current-based sensors:*

To achieve the range of 0 – 2.5V, you must choose a resistor value according to Ohm's Law.

$$V = I * R$$

A resistance, R, must be chosen depending on the sensor output, I, in order to achieve a maximum

voltage,  $V$ , of 2.5V. For example, if a sensor with a current output of 4-20 mA was used (conductivity sensor), we would get this result:

$$2.5V = 20mA * R$$
$$R = 125\Omega$$

Since the minimum output from the sensor is actually 4mA and not 0mA, the minimum voltage reading will be:

$$V = 4mA * 125\Omega$$
$$V = 0.5V$$

This choice of resistor gives us a range of 0.5V – 2.5V.

#### *Resistive-based sensors:*

Resistive output sensors change their resistivity based on the environment they are in. Scaling of the output will be based on a simple voltage divider circuit with one resistor being the sensor and the other being the scaling resistor.

$$V_{out} = \frac{Z_2}{Z_1 + Z_2} * V_{in}$$

In this case,  $Z_2$  is the resistor value we are looking for,  $Z_1$  is the resistive value of the sensor,  $V_{in}$  is the 12V power supply, and  $V_{out}$  is the output voltage that will be sent to the MDA300.

For example, a sensor that changes its resistivity from 4k $\Omega$  to 33k $\Omega$  (temperature sensor) will require the following calculations in order to determine the resistor that will be put in series with it.

$$2.5V = \frac{Z_2}{4k\Omega + Z_2} * 12V$$

$$Z_2 = 950\Omega$$

#### *Connecting a sensor to the mainboard:*

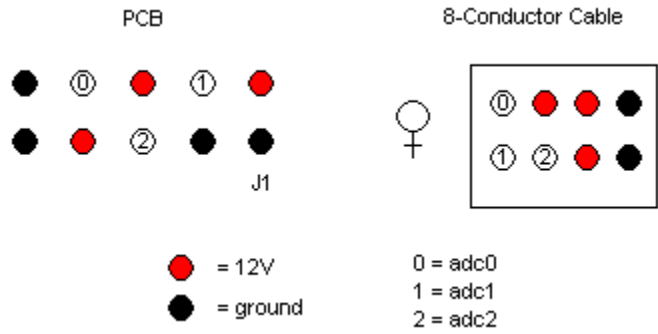


Figure 9: Mainboard and cable connection layout

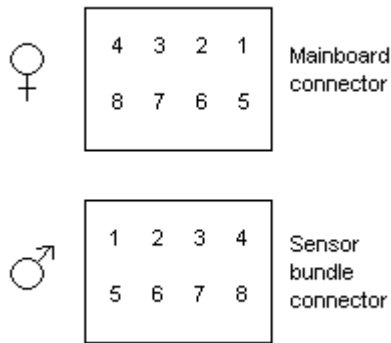


Figure 10: 8-Conductor cable pin numbering

Figure 9 illustrates the layout of the J1 header on the mainboard. 8-conductor cables connect to this header all in the same fashion, which is also shown in figure 9. This allows for all sensor bundles to be used with any node.

### Batteries:

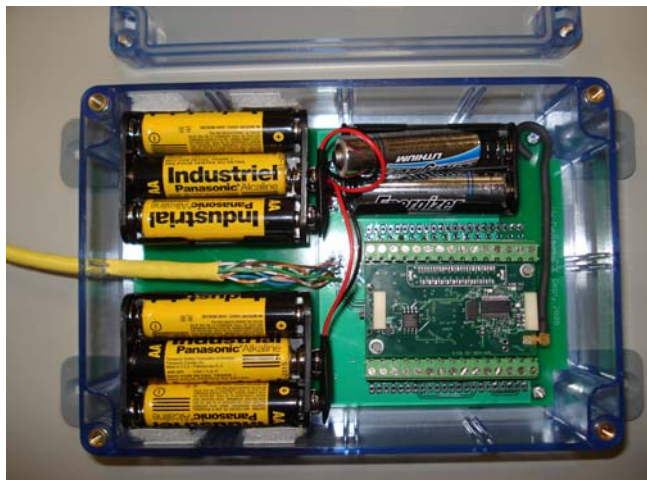


Figure 11: Sensor node with battery packs

*MDA300 and MICA2 Power Source:*

There are two power sources in the node. One battery pack, originally consisting of 2 AA batteries, powers the MDA300 and the MICA2 boards. When the node is not sensing and transmitting, the drain on this battery pack is somewhere in the nA range. The current output when the node is sensing and transmitting is 2-4mA. Thus, the battery life is dominated by how long and how often the node is sensing and transmitting.

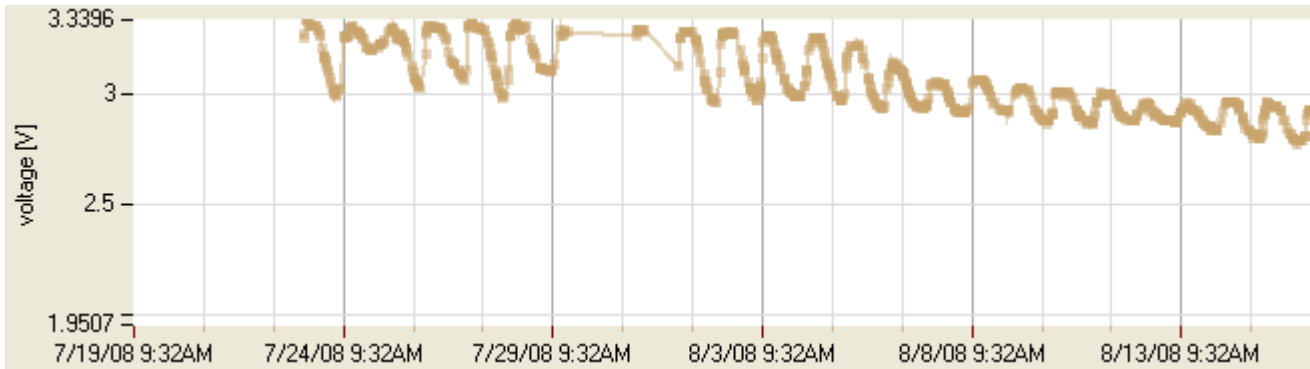


Figure 12: MDA300 and MICA2 battery drain

Nominal input voltage for the MICA2 is 2.7-3.3V. The batteries used in figure 12 were Panasonic AM-3PI alkaline AA batteries. This node was sensing and transmitting for 3 seconds every 3 minutes. The battery drain is linear. This figure illustrates this and shows a corresponding lifetime of approximately 1 month. This life could be extended by extending the intervals in between sensor readings.

We have upgraded this power source by using 2 C-cell batteries in place of the AA batteries. Only minor modifications were needed, but estimated battery life has been extended by roughly 4-fold.

*Sensor Power Source:*

The second power source in the node is the sensor power packs. This consists of 12 AA batteries, generating a maximum voltage of 18V. This, like the mote power source, is dominated by the duty cycle of sensor readings. Figure 13 is a graph of the voltage decay over the course of about a month. This decay is linear and corresponds to a battery life of approximately 3 months. Panasonic AM-3PI alkaline batteries were used to obtain these data.

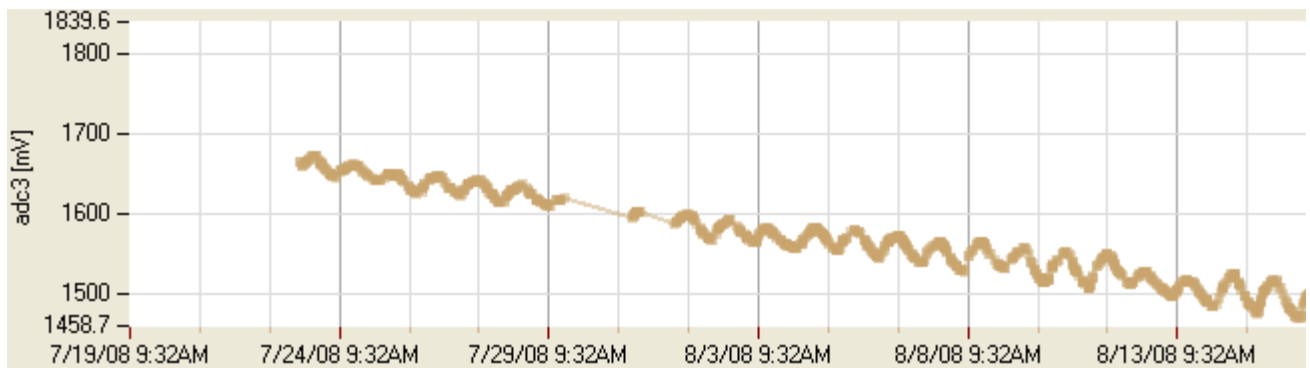


Figure 13: Sensor battery drain

## Field Deployment and Data.

*Catchment 1.* The CrossBow® motes were deployed in the Crystal Bog (CB) catchment, roughly 5 km east of the UW-Madison Trout Lake research station. During the late summer and fall of 2008, we instrumented 5 nodes to monitor changes in water level, temperature and bulk solute concentrations in response to rainfall events, which were also monitored at the study site. The primary purpose was to evaluate the prototype nodes for: 1) field-ruggedness, reliability, accuracy and precision; and 2) power consumption. Our secondary objective was to obtain a first look at the response of the CB lake and wetland to individual rainfall events and the intervening periods of dry-out.

Data on water levels fluctuations from the CB network are shown on Fig. 14. The data show that the sensors are capable of detecting very small changes in lake level and the peatland water table in response to individual rainfall events - even if the events deposit only a few millimeters of rain.

As shown on Fig. 15, the response in the lake and in the peatland was directly proportional to the amount of rainfall that fell in the subcatchment. Both the lake and the peatland responded rapidly to rainfall events, but there was a larger response in the peatland. When one centimeter of rain fell, the lake level rose quickly by about the same amount. However, the water table in the peatland rose by almost two centimeters for each centimeter of rain. During dry spells between rain events, the lake level and the water table both declined gradually, presumably due to evaporation and groundwater flow out of the subcatchment.

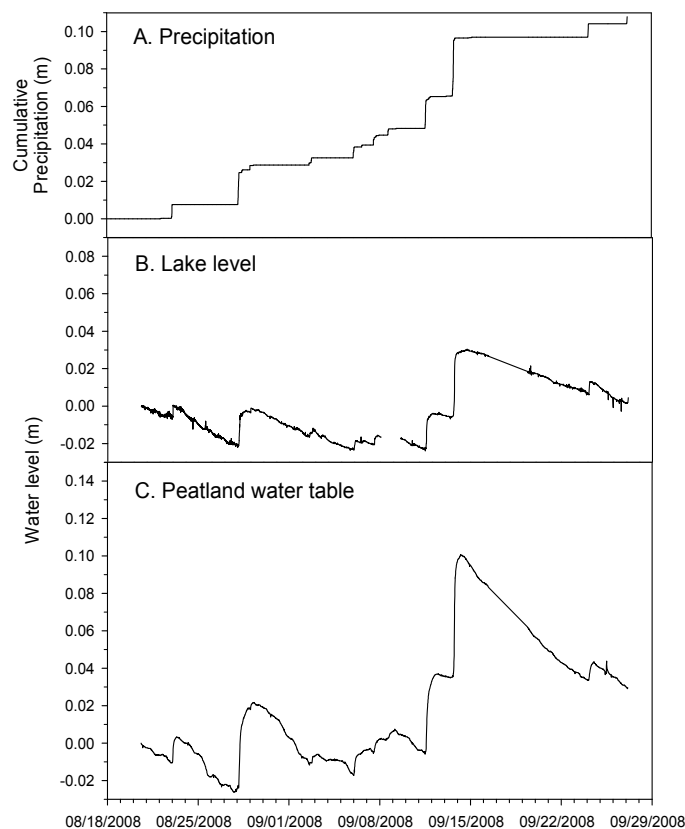


Figure 14. Water flux data from the P2 MOTE network in Crystal Bog, late summer 2008. These data illustrated that the P2 water-level sensors were field-rugged and sufficiently sensitive to discern subcatchment responses to small changes in precipitation and dry-out.

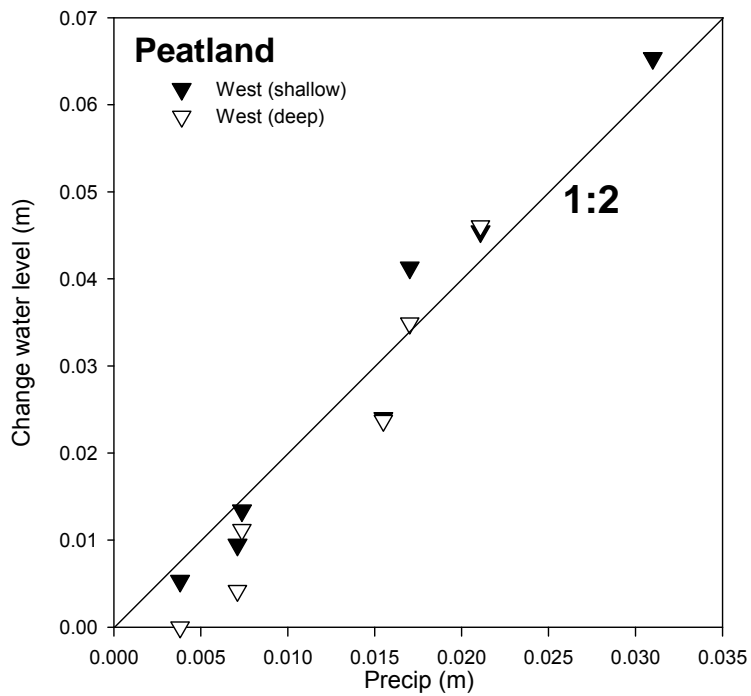
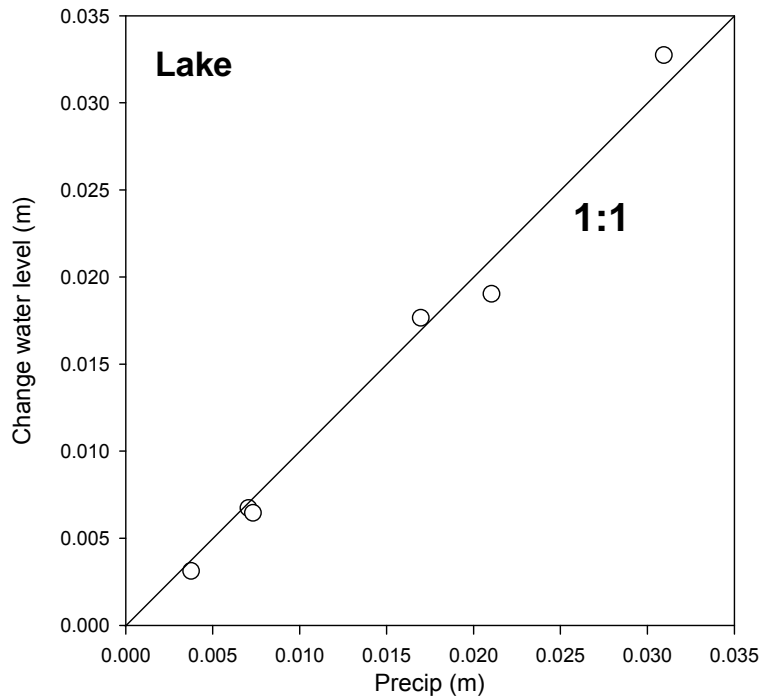


Figure 15. Response of water levels in the CB lake and peatland to precipitation events of various sizes. Note that the response of the lake was 1:1; but the peatland water table responded more strongly to any given event (2:1).

The deployment of monitoring nodes in the CB catchment during 2008 is shown on Figure 16. One node is located in a stilling well within the CB lake to monitor changes in lake water level. Two nodes are located in monitoring wells in the surrounding wetland to monitor fluctuations in the wetland water table. In addition, there is a node to monitor rainfall events. The short-range radios associated with each node communicate with a long-range radio on the GLEON buoy in the middle of CB lake ([www.gleon.org](http://www.gleon.org)). The GLEON radio transmits data back to the Trout Lake research station in near-real time.

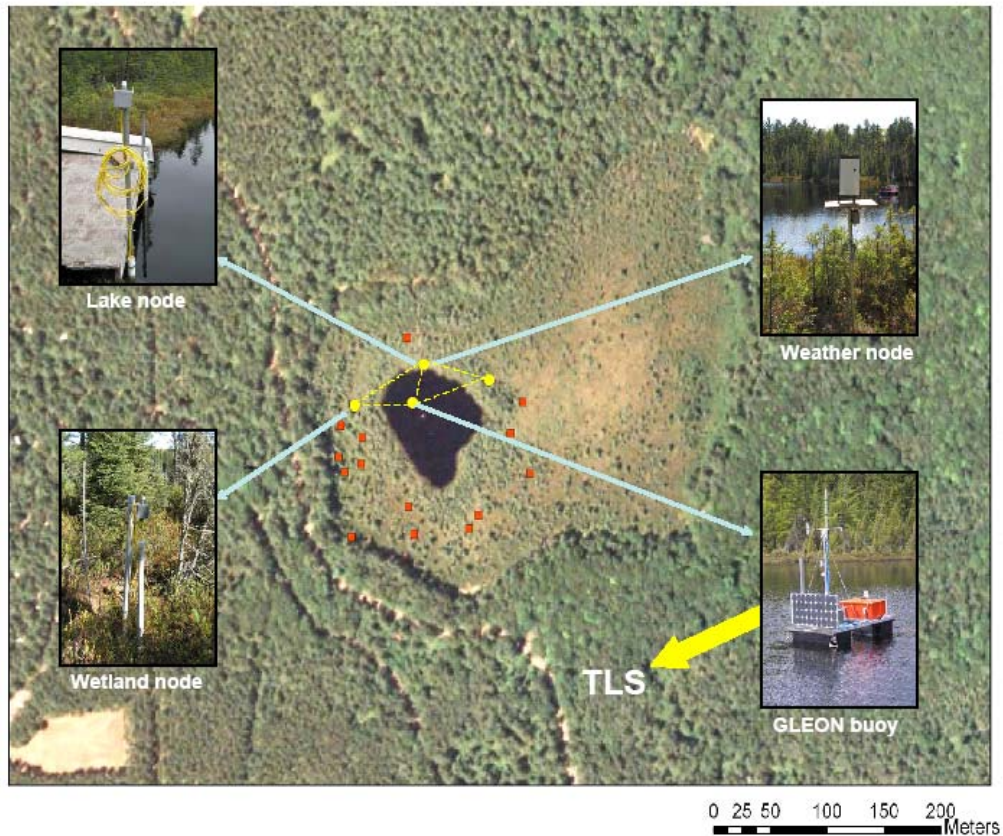


Figure. 16. CrossBow® mote-based monitoring nodes in the CB catchment, NHAL, 2008

During 2009, the spatial distribution of monitoring wells in the CB wetland was modified so that the elevation of the wetland water table could be directly compared to the elevation of the lake. In addition, we installed a node to monitor evaporation using an *in situ* evaporation pan. As the analysis of these new data progresses over coming months, we will be better able to infer hydrologic flowpaths within the catchment; and we will begin constructing seasonal water budgets.

Catchment 2. During 2009, another wetland-dominated catchment (Trout Bog, TB) was selected for the deployment of a second monitoring network comprising commercially available radio sensors (*INW Smart Sensors*, Instrumentation Northwest, Inc.). Nodes in the TB network monitor the same variables as those in the CB network, but the monitoring technology differs. Our objectives are: 1) to compare the performance and cost of the two different technologies, and 2) to compare the hydrochemistry of two different wetlands within the same watershed.

The TB catchment and the CB catchment are both located within the Trout Lake watershed in Boulder Junction. As shown on Figure 17, The TB catchment is near the bottom of the watershed (elevation ~496 MASL) while the CB catchment is near the top (elevation ~502 MASL). In this gently sloping terrain, groundwater and surface water generally flows toward Trout Lake across the contours shown

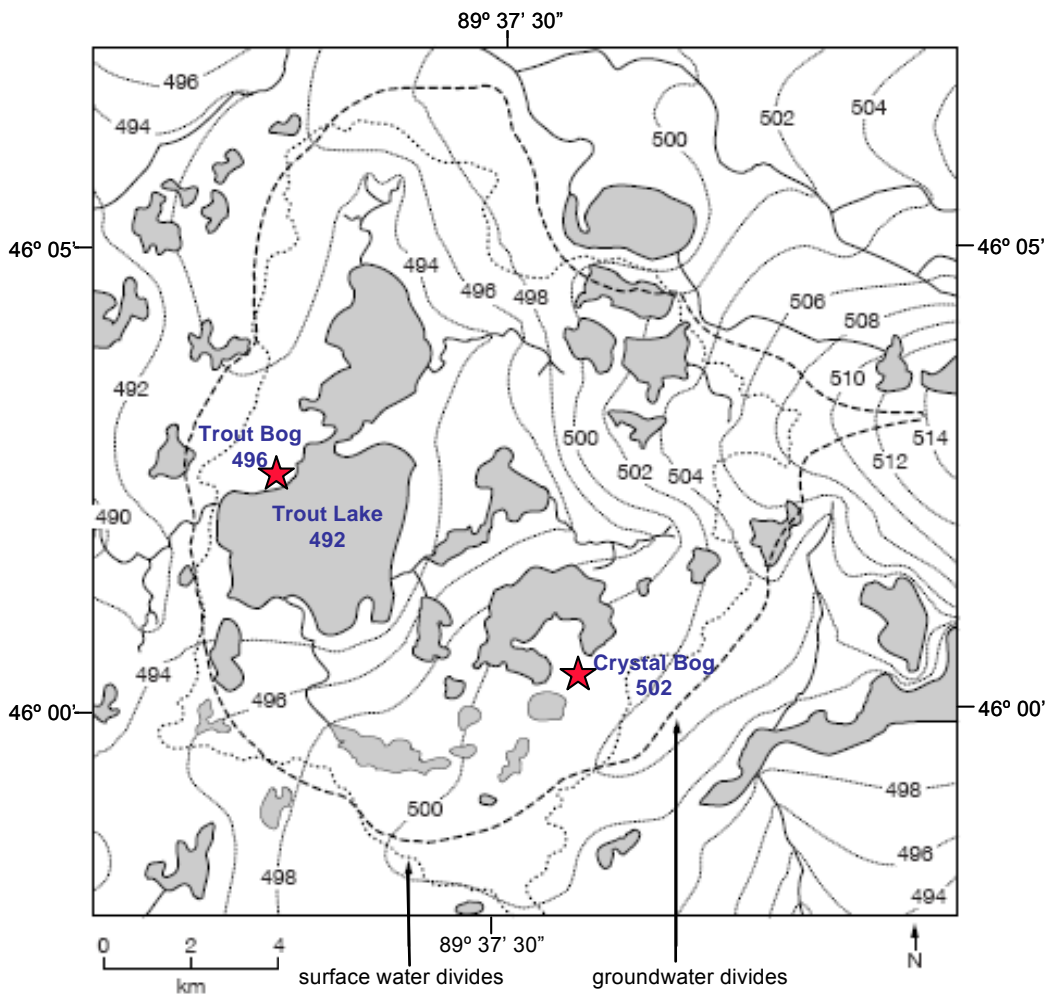


Figure 17. The Trout Lake watershed in northern Wisconsin. Stars indicate the Trout Bog and Crystal Bog sub-catchments.

on Fig. 17. However, hydrologic modeling indicates that local flow-paths are complex and that groundwater actually flows beneath certain lakes. Flow-path variability due to short-term events (weather) and longer term changes (climate) remains uncertain. Long-term monitoring networks will help to constrain this uncertainty

The remote radio-sensors in the TB network can be programmed to form linear networks; but, in contrast to the CrossBow® motes, they cannot form self-healing mesh networks. This limitation constrains the topology and robustness of the INW network, but their commercial availability confers certain advantages. Benefits and costs of the two network technologies will be assessed during continued deployments in TB and CB.



Figure 18 shows a portion of the TB network during 2009, looking from the wetland out toward the bog lake. As with the CB network, the long range radio on the GLEON buoy is being used to transmit data back to the Trout Lake research station in near-real time. At present the TB network is configured with one lake node, five wetland nodes, a rainfall node and an evaporation node.



Figure 18. INW-based monitoring network in the TB catchment, showing two wetland wells and the rain gauge. Red object near center of lake is the GLEON buoy.

During 2009, data was collected from these seven nodes at 30 minute time intervals from June through September. These data are being analyzed during the current phase of FOE-sponsored research.

**Citizen Lake Monitoring Network.** This project also has a public outreach component. We have partnered with the North Lakeland Discovery Center, an environmental NGO in Manitowish Waters, WI, to establish a citizen-based lake level monitoring network across northwestern Vilas county. Many lakes in this region are at record low water levels, a phenomenon that may be linked to our changing climate. Public concern is high, and the citizen-based network was designed to enhance public awareness and understanding of the local water cycle. We trained NLDC staff to install staff gauges and manually collect water level data. In turn, the NLDC recruited and trained volunteers to place gauges on their lakes and record data at weekly intervals. We will continue to work with NLDC staff on data management issues, and we will also help them transition to an automated data collection and management system using technologies similar to those being deployed in the CB and TB catchments.

**Conclusions.** New remote sensing technologies provide an opportunity to better monitor, understand and predict changes in Wisconsin watersheds as our climate evolves over coming years. The primary goal of this project is to design an effective and efficient monitoring network based on these new technologies for broader deployment across Wisconsin's northern highland lake district.