ENVIRONMENTAL AND ECONOMIC RESEARCH AND DEVELOPMENT PROGRAM

Impacts of Climate Change on Fluxes of Carbon and Water in Northern Wisconsin Lakes and Wetlands

Final Report
August 2013

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This report was funded through the Environmental and Economic Research and Development Program of Wisconsin's Focus on Energy.

FINAL PROJECT REPORT - EXECUTIVE SUMMARY

Date: 29 October 2012

Title of Project: Impacts of Climate Change on Fluxes of Carbon and Water in northern Wisconsin Lakes and Wetlands (EERD Research, Project code 3104-01-09)

Investigators: Carl J. Watras, Research Scientist
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Research Category: Environmental and Economic Impacts of Climate Change in Wisconsin Due to Electricity or Natural Gas Use: understand the flux of carbon within Wisconsin's environment, and the ramifications of this understanding for policy development (impacts of climate change on air quality, water quality and forest of agricultural land management.)

Full Project Period: February 2009 through June 2012

Object of Research: Predicted changes in Wisconsin's climate have several implications for our water resources. Precipitation inputs to our lakes, streams and wetlands may increase by as much as 10%, with intense storms generating more runoff. Seasonal precipitation patterns are expected to shift, with less in summer and more in winter. Summer heat waves are expected to become longer and hotter, and night-time winter temperatures may be more moderate. This scenario could trigger more frequent flooding events, more severe summer droughts and higher rates of evaporation. These climatically-induced changes in regional water budgets would also affect fluxes of carbon in lakes and wetlands, potentially exacerbating the greenhouse warming effect. With warmer temperatures, more flooding events and extended dry periods, it is possible that the mobilization of carbon now stored in peatlands will increase significantly. However, the timing and magnitude of carbon export from peatlands to aquatic systems and the atmosphere is difficult to quantify because we lack the data to calibrate predictive models that couple carbon and hydrology in northern Wisconsin.

The object of this research project was to further develop technologies to monitor the fluxes of water and carbon in our lakes and wetlands. It built upon two prior studies still underway in northern Wisconsin. In one prior study (funded by FOE), we developed new technologies to remotely monitor the short-term and long-term effects of rainfall and drought on water fluxes. In a second study funded in part by the National Science Foundation, limnologists at UW-Madison developed methods to remotely monitor internal carbon fluxes in lakes over similar time scales. Here we proposed to link these projects and to develop new technologies to monitor carbon fluxes between lakes and their adjoining wetlands. The resultant data would be applicable to models of the regional carbon cycle and the potential impacts of climatic change.

This project was a cooperative research effort by the Wisconsin Department of Natural Resources (WDNR) and the Center for Limnology, UW-Madison (CFL), in association with the UW-Madison Department of Electrical and Computer Engineering (ECE).

Summary of Key Accomplishments: Two wireless sensor networks (WSNs) were developed and deployed in separate wetland-dominated catchments within the Trout Lake watershed of Vilas County, Wisconsin. Both WSNs were built on low-power micro-processor radio systems (MPRs) that formed an array of sensor nodes embedded in the study catchments to collect data on surface water levels, evaporation, precipitation, peatland water tables, bulk ionic solutes, chromophoric dissolved organic carbon and water temperature continuously at 30 minute time intervals. The sensor nodes were designed to run unattended on battery power for months. They communicated via radio-frequency (RF) signals (rather than wires) through a gateway node to a distant base station.

Based on data collected during wet and dry seasons in the two study catchments, we report highly resolved water budgets (sub-hourly time-steps), transient reversals of hydrologic flowpath, patterns of evapo-transpiration (ET) in peatlands, evaporation rates from surface waters (E), and the temporal dynamics of dissolved organic carbon (DOC, the major solute in many peat-dominated systems). The data indicate that direct precipitation, ET and E dominated the hydrologic budget of both study wetlands, despite their relatively flat geomorphology. Rates of ET from peatlands were comparable to E from open waters but were more variable temporally and more challenging to constrain spatially. Exchange between open waters and riparian peatland varied with antecedent conditions. Precipitation events and intervening periods of dryout caused frequent flowpath reversals across the riparian boundary in both wetland systems, suggesting that flux of solutes, such as dissolved organic carbon, has commensurate complexity.

Field results demonstrate the utility of WSNs in obtaining continuous data on wetland hydrology and bulk water chemistry that can be displayed in near-real-time at a remote location. With respect to technology needs, future wetland observatories would benefit from the further automation and standardization of data handling protocols. Data management, processing and dissemination pose a major challenge because the volume of data from embedded sensor networks can grow rapidly. With respect to wetland science, WSNs show considerable promise. Several challenges remain, however, such as the construction of comprehensive water budgets for peatlands where the spatial variability of critical variables like ET and lateral flow is high. The integration of direct hydrological methods with indirect methods based on energy balance models and micrometeorological techniques is likely going to be essential. With respect to the issue of climatic impacts on wetland ecosystems, data from wetland observatories can facilitate hypothesis testing and the refinement of local and regional climate models. Flashier water tables and gradually declining lake levels may result from a future climate that is both warmer and wetter. If the mobilization of peatland carbon depends on the frequency and magnitude of water level changes, then carbon fluxes between terrestrial, aquatic and atmospheric pools may also be affected, feeding back positively on the warming effect. Wetland sensor networks constitute a useful tool for tracking such climatic impacts over both short and long time-scales. We conclude that the wider deployment of wireless wetland observatories would help to validate and refine environmental hydrologic and carbon cycling models and to foster collaboration that would improve the science of climatic impacts on sensitive water resources.

As an adjunct to the two WSNs, we partnered with a local environmental NGO to develop a parallel Citizen Science Water Level Monitoring Network that trained 26 local volunteers to monitor water levels manually in 26 lakes at weekly time intervals. The purpose of this parallel network was to raise citizen awareness and to augment the high-frequency WSN data with low-frequency data collected over a larger number of water bodies. Volunteer retention has been 100% for 3 years, and coordination with the Wisconsin SWIMS database has been initiated.

Future Research Directions: Data collection from both WSNs will continue for the foreseeable future. Opportunities for introducing WSN technology into the Citizen Science program will be explored.

List of Acronyms

CB	Crystal Bog
CFL	Center for Limnology, University of Wisconsin-Madison
DAQ board	data acquisition board
DOM	dissolved organic matter
ECE	University of Wisconsin-Madison Department of Electrical and Computer Engineering
EERD	Environmental and Economic Research and Development Program of Wisconsin's Focus on Energy
ET	evapo-transpiration
GLEON	Global Lake Ecological Observatory Network
NHLD	Northern Highland Lake District
QA/QC	quality assurance and quality control
RF	radio frequency
SWIMS	Wisconsin Surface Water Integrated Monitoring System
TB	Trout Bog
TLS	Trout Lake Station
WDNR	Wisconsin Department of Natural Resources
WSN	wireless sensor networks

FINAL PROJECT REPORT

To
Kathryn Eggers, Program Manager
Focus on Energy EERD Program

From
Carl J. Watras, Research Scientist
Wisconsin Department of Natural Resources

Project Title: Impacts of Climate Change on Fluxes of Carbon and Water in northern Wisconsin Lakes and Wetlands (Project code 3104-01-09, EERD Research)

Full Project Period: February 2009 through June 2012

Background, Objectives and Approach

In this project, we proposed to develop and deploy embedded radio-sensor technologies (WSNs or wireless sensor networks) to enable the monitoring of climatic effects on fluxes of water and carbon in northern lakes and wetlands. The project was a cooperative research effort by the Wisconsin Department of Natural Resources (WDNR) and the Center for Limnology, UW-Madison (CFL), in association with the UW-Madison Department of Electrical and Computer Engineering (ECE). The field sites were two wetland-dominated sub-catchments in the Trout Lake watershed of Vilas County, Wisconsin: Crystal Bog (CB) and Trout Bog (TB).

For northern Wisconsin, climate models predict that annual precipitation will increase by ~10% (with most of the increase occurring in winter), summer heat waves will be longer and hotter, and winter temperatures will become more moderate due mainly to an increase in night-time minima (WICCI, 2011). These projections suggest that the amplitude of regional water cycles may increase due to larger inputs (rain and snow) and larger losses (evapo-transpiration). However, the net effect on regional water balances remains uncertain because inputs and losses may cancel in a future that is both warmer and wetter. There are few observational studies relating the intensity of sudden storms and heat waves to the balance between precipitation, evapo-transpiration and terrestrial water storage over seasonal, annual or decadal time-scales. Although modeling can constrain impacts based on assumed parameter values, the timing and likely magnitude of effects are difficult to predict without sufficient data for model calibration and validation.

For water resources, it is likely that the impacts of extreme weather will be most severe in small catchments that comprise wetland complexes. These catchments are especially vulnerable to climate due to their shallow depth and high rates of evapo-transpiration (Rosenberry and Winter, 1997; Kundzewicz et al., 2007; Mackay et al., 2007). Modeling studies indicate that wetlands are among the least resilient ecosystems under future climate scenarios (Johnson et al., 2004; 2005). Reductions in hydroperiod could severely impact amphibian and waterfowl populations that now inhabit these systems as permanent or migratory residents. Impacts on water quality would also be expected if the exchange of solutes across riparian boundaries was altered by warmer temperatures, more flooding events and extended dry periods, One result could be the mobilization of organic carbon now stored in peatlands, potentially exacerbating the greenhouse warming effect (Evans et al., 2006; Ise et al., 2008; Dorrepaal et al., 2009). However, predicting changes in carbon export from peatlands will require a better understanding of the geochemical coupling between the carbon and water cycles.

The main objective of this project was to develop and deploy new sensing technologies that could provide some of the data needed to test current hypotheses and to refine, calibrate and validate existing models of climatic impacts on water resources. Remote sensing networks and IT platforms were designed to acquire, validate, archive, and disseminate site-specific data on precipitation, temperature, evaporation, transpiration, water storage, organic carbon and bulk ionic solute concentrations over time scales ranging from minutes to decades. High frequency measurements were considered necessary to quantify the impacts of episodic, intense events and to identify causal mechanisms. Longer time scales are needed to assess sustained impacts and future trends. Two different sensor networks were deployed as "Wetland Observatories" to evaluate alternative technologies.

The study region was the Northern Highland Lake District (NHLD) in northern Wisconsin and upper Michigan, a 6400 km^2 region rich in lakes and wetlands (Buffam et al., 2011). Several factors made this an appropriate site for investigating climatological impacts on water resources. First, the region is relatively pristine; so the confounding influence of the built environment and landuse change is low. Second, the NHLD typifies circumpolar, temperate/boreal landscapes that are tightly coupled with their regional water cycles and highly vulnerable to climate change (Cardille et al., 2007). The region is characterized by low topographic relief, extensive forest cover, thousands of lakes and abundant wetland. Lakes and wetland cover about 13% and 20% of the land surface area, respectively (Webster et al., 2006; Buffam et al., 2011). The wetlands store an estimated 144 ± 21 Tg C in deep peatlands - an amount that is 130% larger than the mass of carbon stored in the upland soils and forest biomass combined (63 ± 3 Tg C) (Buffam et al, 2010).Third, the NHLD has a long history of water resources research and an extensive historical database on water quality, water quantity and weather (e.g. Magnuson et al., 2006). It is currently the NSF-designated site for long-term ecological research on northern temperate lakes (http://lter.limnology.wisc.edu/), and it is the primary North American site in the Global Lakes Ecological Observatory Network (www.gleon.org). The NADP-NTN meteorological site on Trout Lake (WI-36) has been collecting high quality data on weather and climate for several decades in collaboration with the Bureau of Air Management, WI DNR (http://nadp.sws.uiuc.edu/NTN/, http://dnr.wi.gov/air/).

NHLD landscape in northern Wisconsin

The project built on two prior studies in which we designed and deployed a small prototype WSN in one of the two study catchments (FOE Grant Nos. 07-04 & 08-12). Working closely with Professors Yu Hen Hu and Michael Morrow, Department of Electrical and Computer Engineering (ECE), UW-Madison, and two ECE undergraduate students, we built a prototype that transmitted data from Crystal Bog back to the Trout Lake Station (TLS) at 15 to 30 minute intervals. The hardware platform for each node in the network consisted of a MDA300 data acquisition board (DAQ board) and a MICA2 mote from Crossbow Technology (Fig 1). These devices were interfaced with sensors via a printed circuit board designed at ECE.

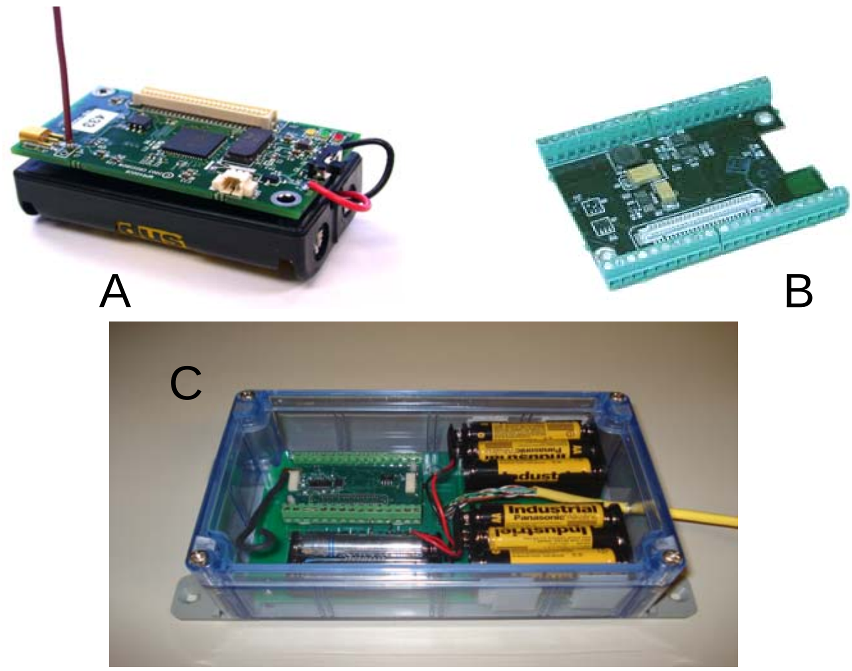

Figure 1. Hardware platform for the wireless sensor network in the CB catchment (FOE-funded MOTE project). A. MICA2 mote;B. MDA300 DAQ board; C. fully assembled node with batterypacks and cable to sensors.

These small sensing devices were coupled with a larger monitoring network called GLEON (Global Lake Ecological Observatory Network; http://GLEON.org), which is a world-wide network of sensor buoys collecting limnological data on lakes and transmitting it via high-power radio to remote servers where it can be shared with other labs via the Internet. Our prototype MOTE network transmitted short-range RF signals to the GLEON system which then relayed the data to TLS, as illustrated on Fig. 2. In addition to advanced RF technologies, GLEON brought several other proven methodologies to our project, including:

a. Automated data acquisition and information management (IM) through standards and a suite of tools
b. Integration of sensor data with other data sources
c. Tools for easily publishing and accessing the data
d. Tools for data QA/QC, data visualization, and export to models.

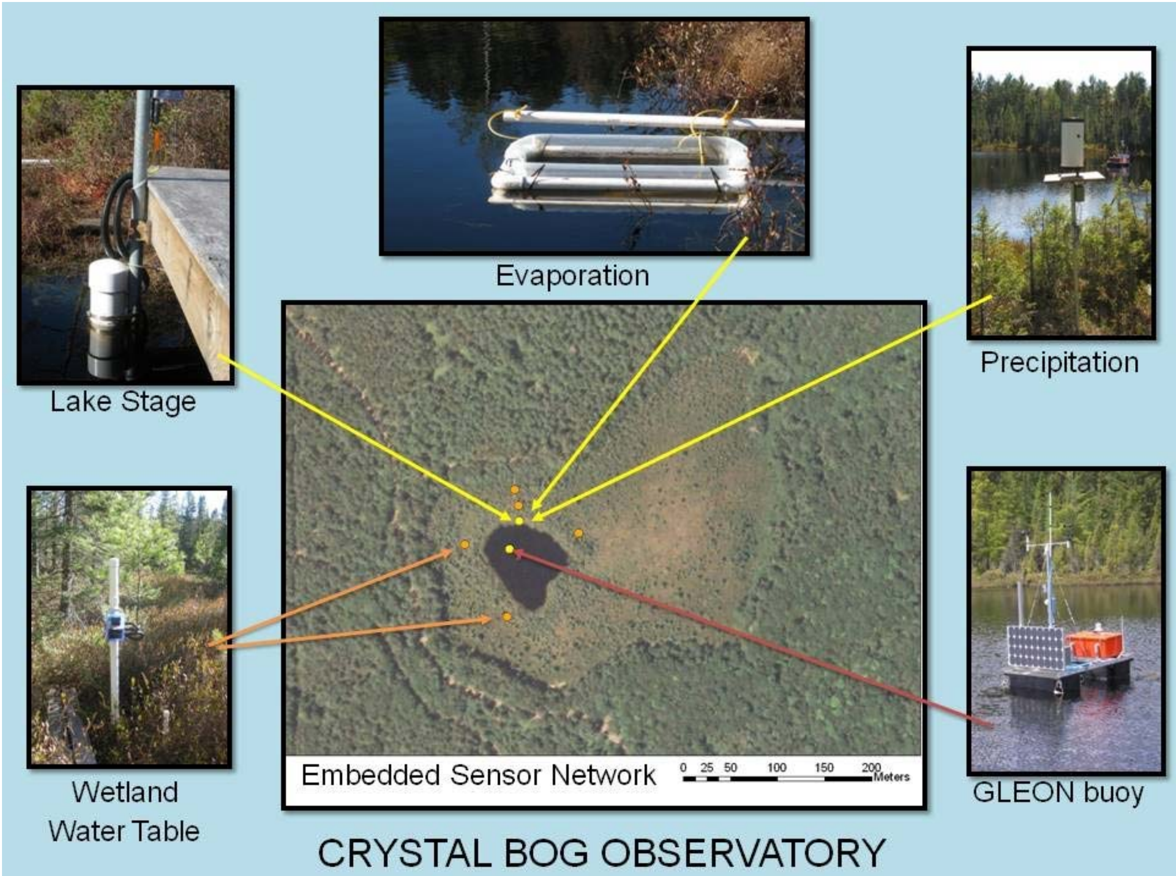

Figure 2. Crystal Bog catchment in Vilas County showing components of the FOE-funded MOTE sensor network and the GLEON sensor buoy. These two remote monitoring systems are now coupled to send environmental data for the lake and the wetland back to Trout Lake Station (TLS) via radio telemetry for viewing in near-real time. There are currently five wetland nodes in the MOTE network (water table) in addition to the precipitation node, evaporation node and the lake level node .

An important task of this project was to embed new sensors into the MOTE and GLEON networks so that the dynamics of organic carbon and water could be monitored simultaneously over multiple time-scales. The purpose was to increase our understanding of the exchange of carbon and water between peatlands, lakes and the atmosphere as a function of weather and climate. The approach was to build on the prototype technology which showed substantial promise. An example of data from the prototype network is shown on Fig. 3. These data showed that the sensors could detect very small changes in the lake level and the water table in the peatland in response to individual rainfall events - even if the events deposit only a few millimeters of rain. As shown on Fig. 3, the response in the lake and in the peatland was directly proportional to the amount of antecedent rainfall. 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. The high degree of resolution in the MOTE data was promising, and it strongly suggested that our current methods were suitable. The proposed new network sensors were designed to detect organic carbon emanating from the peatland surrounding the bog pond. This type of organic carbon has a fluorescence signature that the sensors can measure optically. To incorporate these sensors, the existing network was enhanced and new connections were made between MOTE and GLEON.

A second task for this project was to develop a second prototype network in a similar, nearby catchment using commercially available technology. The purpose was to compare the performance and cost of the two technologies under similarly rigorous field conditions. The second field site was Trout Bog, located about 5 km from Crystal Bog but in the same general watershed. At this site, a WaveData® Wireless data collection system from Instrumentation Northwest, Inc. (www.inwusa.com), was installed. Each INW smart sensor is equipped with internal data-logging capabilities, and the on-board micro-controller can be programmed to support multi-phase logging and communicate over either Modbus® or SDI-12 protocols. Data can be downloaded manually from each sensor node, or as in our application, WaveData® radios can communicate data to a hub node via low-power RF channels (0.01 watt) broadcasting on demand at ~900 MHz. Both embedded sensor networks were to be optimized for power efficiency and cost efficiency to facilitate deployment at multiple sites and remote locations where they could function for months with low or no maintenance. The IT infrastructure would eventually be configured to facilitate data access across a broad science network.

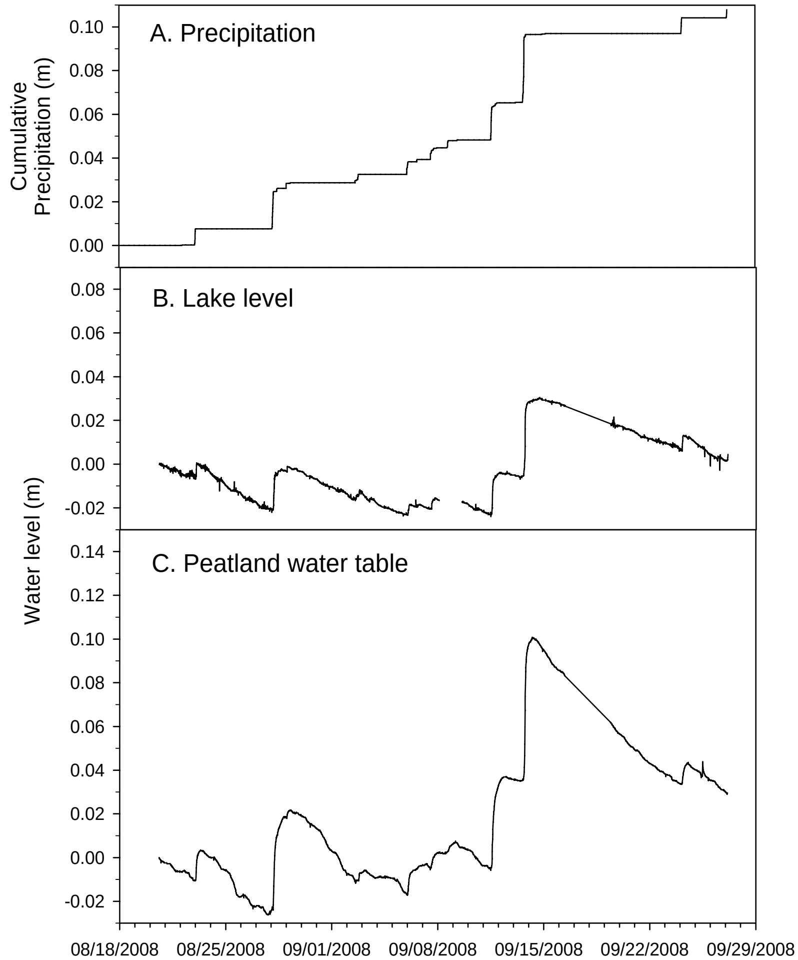

Figure 3. Hydrologic data from the 1st prototype MOTE network in Crystal Bog, autumn 2008 (15 minute data).

A third task was to initiate a Citizen Science Network of volunteer monitors to acquire data on water levels in various lakes using manual instead of automated techniques. The costs and efficacy of manually collected data could then be compared with the high frequency data collected by the WSNs. This task involved forming a partnership with the North Lakeland Discover Center, a NGO that provides environmental education to local schools and citizen groups. At some future point, the Citizen Science Network could then evaluate the efficacy of establishing a public WSN based on the technologies used in our wetland catchments.

A forth task was to make the technology and monitoring results available through a project webpage and through technical reports and presentations.

With these four major tasks in mind, the anticipated results from this project were: 1) two fully-functional WSNs and IT infrastructures that would serve as technological models for wider deployment across multiple spatial scales; 2) a continuous stream of high-quality, spatially and temporally integrated hydrochemical data from representative wetland sites that would be broadly available to the scientific community for analysis and interpretation; 3) a citizen science network that could eventually use these technologies (or alternatives) in the public domain;4) a project webpage that could be updated periodically and publicly accessed as well as technical papers in the peer-reviewed scientific literature and presentations at scientific and public meetings.

Accomplishments.

Water Table Dynamics. Both sensor networks provided highly resolved time-series on water table fluctuations in peatlands during the ice-free season. Hydrographs from both WSNs show that the embedded sensors could resolve millimeter-scale changes in water level resulting from small rain events or a few hours of dry weather. Early data from Crystal Bog were shown above in Figure 3, and data from the commercial WSN in Trout Bog are shown on Figure 4. In both cases, the data shown were downloaded directly from sensors, without smoothing or other signal processing; and they illustrate the low signal:noise ratio that is typical of sensor nodes in both networks.

The time-series for TB on Figure 4 shows that the peatland water table rises rapidly during rain events and then declines gradually after the rainfall stops. As a result, the hydrologic gradient between the peatland and pond changes frequently and in a site-specific way. For example, during heavy rain events in summer, a transient water table mound developed at peatland site P1.5. The duration of the mound was short (1 to 4 days per event), but the water table occasionally rose to a higher elevation than the bog pond so that the hydrologic gradient was reversed. A more significant change in hydrologic gradient was observed at near-shore site P3 where the water table rose abruptly to elevations several cm above pond level for 2 to 3 days after some rainfall events. In contrast, the water table at near-shore site P5 rose gradually to levels ≤ pond stage during the same rain fall events (Fig. 6F). These contrasting patterns suggest that water periodically pulsed into the pond from site P3 and flowed out of the pond toward site P5. Site P5 is adjacent to the 45m-wide isthmus separating the Trout Bog pond from Trout Lake, which lies at an elevation ~1.8m below the pond.

This episodic hydrologic behavior is only observable with high-frequency data collection systems, such as the WSNs. It occurred in both TB and CB; and hydrologically, it suggests that direct precipitation was the major source of water to the wetland complexes for the entire open-water season. The absence of a delayed water table rise following precipitation is characteristic of ombotrophic wetlands because recharge by a deep groundwater system would necessarily be accompanied by a time delay due to inflow after the cessation of precipitation (Hemond, 1980). Although the both wetlands are topographically situated below elevated uplands, and although the peatlands are not obviously domed or sloped toward a conspicuous lagg or stream (cf. geophysical models of Ingram (1982) or Holden and Burt (2003), they do appear to be perched above the local groundwater system. Pending a detailed flow-net analysis, we hypothesize 1) that groundwater from the upland flows beneath the wetland complexes, as observed for many kettle lakes situated in the NHLD's deep glacial till and outwash sand (e.g. Webster et al., 2006), and 2) that flows within the wetlands are complex but dominated by lateral transport in the upper layer of peat.

Evapo-transpiration (ET). The hydrographs shown on Figure 4 show another conspicuous feature that is only visible with high frequency data. During periods of water table drawdown between rain events, the hydrographs at some sites exhibit distinct diurnal oscillations that appear as ripples or waves. The oscillations, which are first evident in hydrographs during leaf-out in early May and then amplify during summer, result from evapo-transpiration within the peatland. The properties of the diel oscillations can be used to estimate rates of transpiration by wetland plants.

To estimate evapo-transpiration rates from specific sites, we used the modified White (1932) method for deconstructing diurnal water table fluctuations. The method permits sub-daily estimates of ET (given precise, high-frequency water table data) by decomposing daily fluctuations into two processes: 1) a drawdown during daylight hours due to consumption by vegetation and 2) a continuous refill due subsurface inflow. ET estimates were obtained using the following equation from Loheide (2008):

$$ET_G(t) = S_Y^* \left[\Gamma\left(WT_{DT}(t)\right) + m_T - \frac{dWT}{dt} \right]$$

where $ET_G(t)$ is the rate of water loss from the saturated zone due to transpiration (L/T), S_Y^* is the readily available specific yield of the peat (dimensionless), *dWT/dt* is the rate of change in water table depth (L/T), and the remaining terms constitute the net inflow (recovery) rate (L/T) for a detrended water table. In this study, Sy* was estimated using the precipitation infiltration method wherein the relationship between ΔWT and precipitation amount was established as an empirical function of water table depth (Rosenberry and Winter, 1997; Gerla, 1992). This approach is suitable for wetlands due to high vadose moisture, shallow water tables and negligible overland flow (Loheide, 2008)

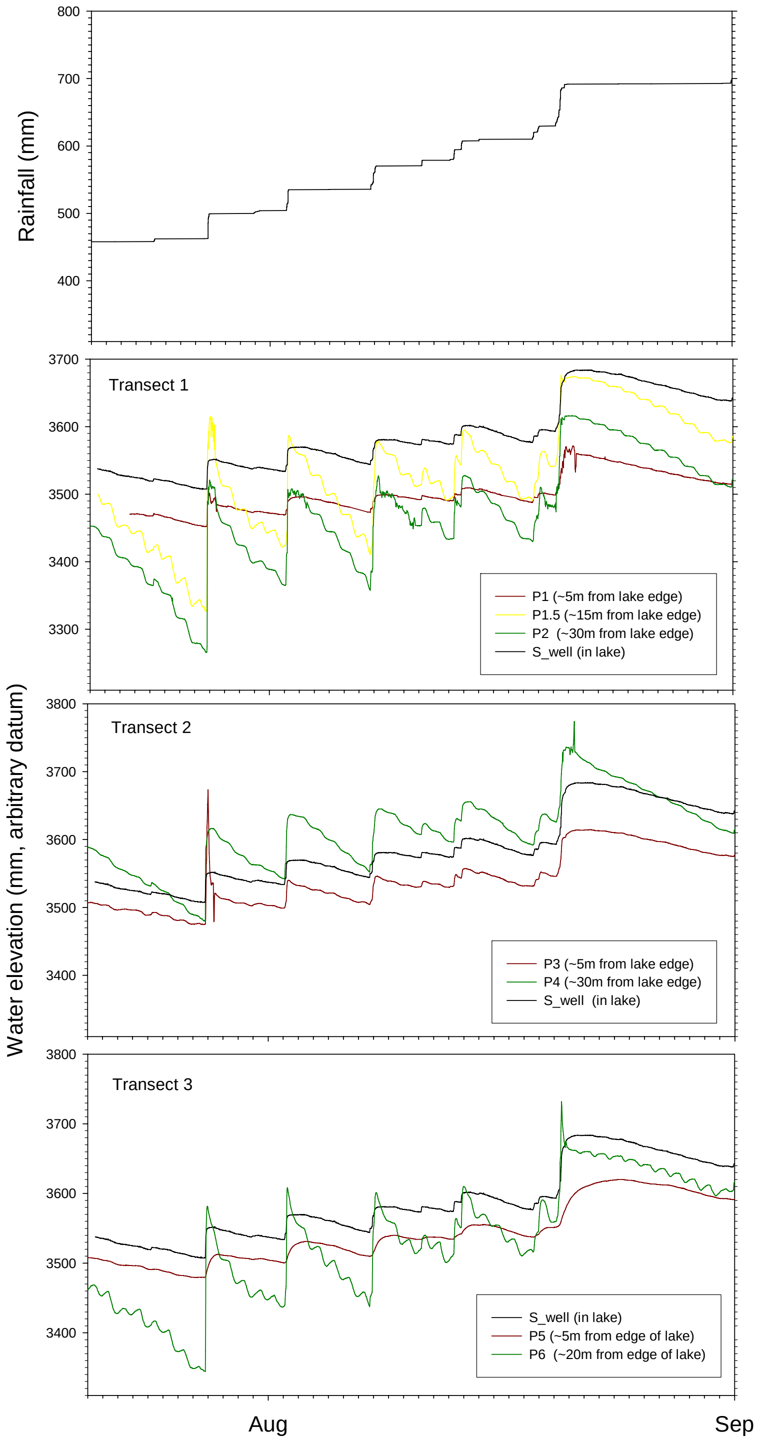

Figure 4. Hydrographs from the Trout Bog WSN.

For the Trout Bog peatland, our estimates of ET averaged 4.8 mm/day (range: 2.2 to 9.1 mm/day) across all sites. This rate of water loss was higher than the evaporative loss from the bog pond (3.4 ±1.3 mm/day, mean ±range), an observation that points to the importance of transpiration by plants as a driver of the peatland water balance.

CDOM Dynamics. Bog lakes typically have tea-stained water due to inputs of dissolved organic matter (DOM) from the surrounding peatland. The CDOM sensors were deployed to monitor changes in DOM over short time-scales as an indicator of the carbon flux across riparian boundaries. To ensure the quality of CDOM data, the effects of potentially confounding environmental variables on the sensors, like temperature and ambient light, were first evaluated in a series of experiments. Laboratory experiments with two *in situ* fluorometers showed that CDOM fluorescence intensity decreased as ambient water temperature increased. A temperature compensation equation was derived to standardize CDOM fluorescence measurements to a specific reference temperature. The form of the equation is: $CDOM_r = CDOM_m/(1 + \rho(T_m - T_r))$, where T is temperature (^oC), ρ is the temperature-specific coefficient of fluorescence ($^oC^{-1}$), and the subscripts r and m stand for the reference and measured values. An analogous function is used widely to calculate temperature-specific conductance from the measured conductivity of natural waters. For the two sensors we tested, the temperature-specific fluorescence coefficients (ρ) were -0.015±0.001 and -0.008 ±0.0008 for Wisconsin bog waters at 20 ^oC. When applied to field data, temperature compensation removed the effect of multi-day trends in water temperature Watras et al., 2011).

We also investigated the effect of diurnal changes in sunlight on the CDOM sensors because, hypothetically, stray light might introduce a diel artifact. To test this hypothesis, we placed a light-shielding flow-through cap on one sensor, and then we deployed it alongside an unshielded sensor in Crystal Bog. Water was pumped through the flow-cap using a submersible mini-pump. The results showed that the CDOM readings were similar between the shielded and unshielded fluorometers (Watras et al., 2011).

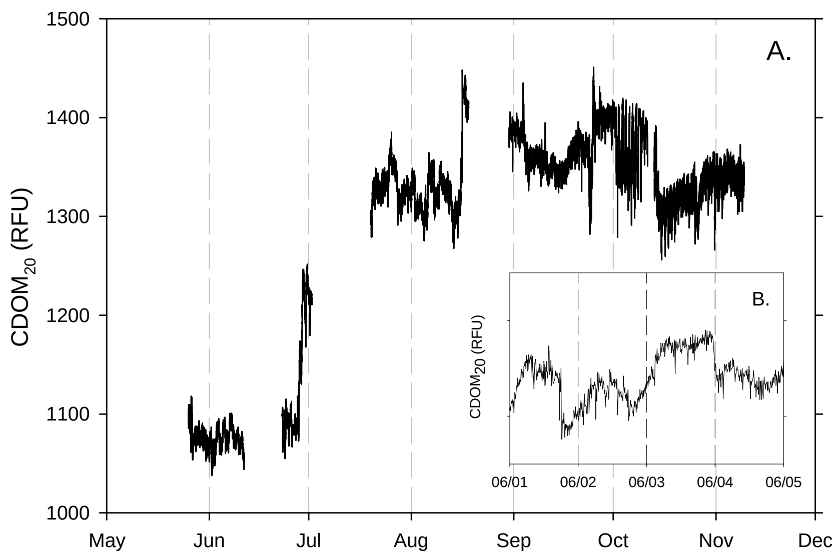

Figure 5. Time-series for CDOM fluorescence in the CB pond (data referenced to a standard temperature of 20 ^oC)

As indicated by field data shown on Figure 5A, the concentration of DOM was relatively low in CB during the dry spring weather, but it increased by ~30% after the rainy period began in mid-June 2010 – presumably due to export from the surrounding peatland.

Plotted on a finer time-scale, the CDOM fluorescence exhibits a diurnal cycle similar to that observed in other freshwater studies (Fig 5B; cf. Spencer et al., 2007; Pairie et al, 2010; Sandford et al., 2010). Although the cause of the daily CDOM oscillation remains unknown, further studies may provide insight into the dynamics of wetland carbon. Our prior experiments with these sensors indicate that the diel CDOM cycle is not a direct effect of diurnal changes in water temperature or the effect of sunlight on the fluorescence sensors. Hypothetically, it might reflect a diurnal change in vertical mixing within surface waters, the reversible photo-bleaching of DOM or microbial activity cycles. If daytime photo-oxidation or bacterial metabolism prove to be causal factors, it would imply rapid cycling of DOM in surface waters and a potentially large back-flux of gas-phase carbon to the atmosphere. Absent a time-series of high frequency sensor data, this phenomenon is invisible to investigators

<u>Water Budgets</u>. Since there are no surface inflows or outflows from either wetland complex, water budgets for the two bog ponds were based on the water balance equation: $\Delta S = (P - E + G_{net})$, where ΔS represents the change in storage, P is direct precipitation onto the pond surface, E is evaporation and G_{net} is the net subsurface exchange between the pond and the peatland. The variables ΔS, P and E were measured directly and G_{net} was estimated by difference.

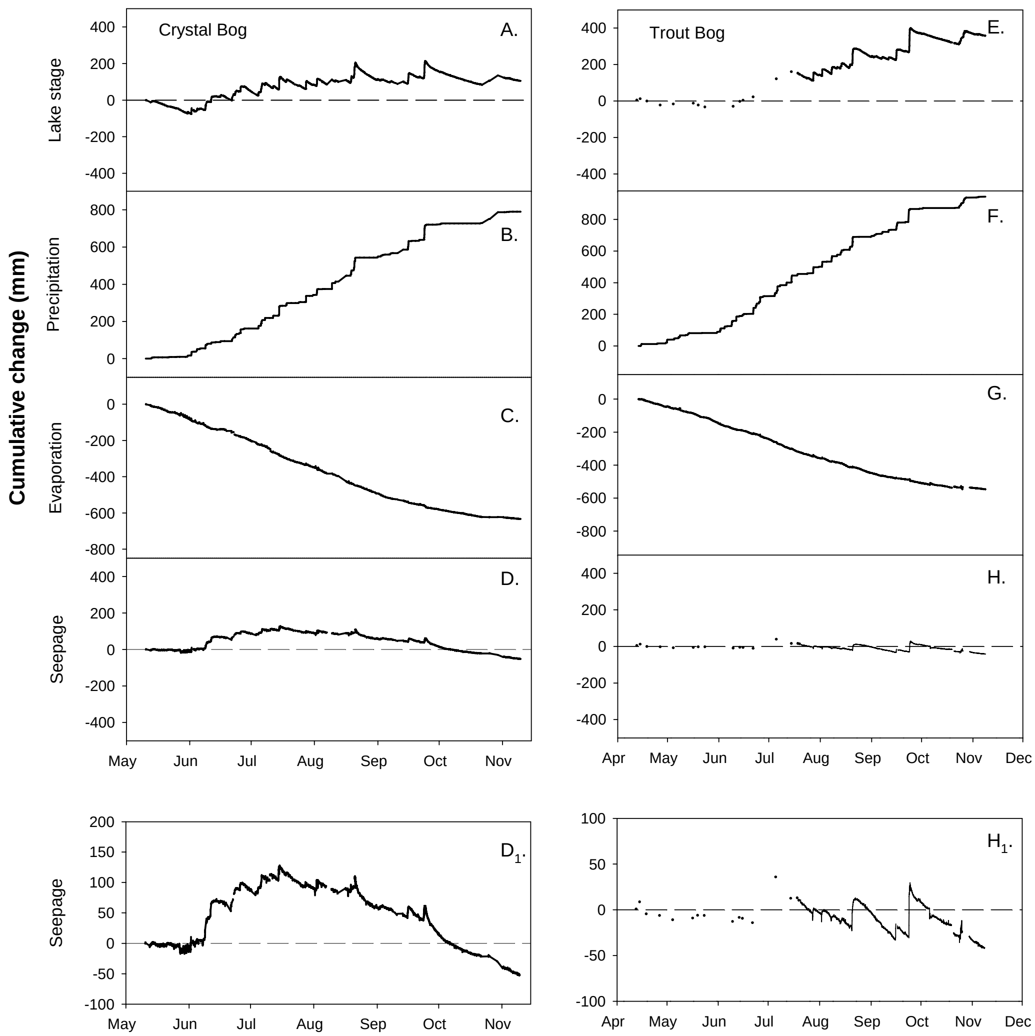

Figure 6. Components of the water budgets for the two bog ponds based on highly resolved sensor data (CB:15 minute intervals; TB: 30 minute intervals). Note: panels D_1 & H_1 same as D & H but with expanded scale.

Given the 15 to 30 minute frequency of sensor measurements, it was possible to construct budgets for the bog ponds at very fine time-scales (Figure 6). The highly resolved water budgets indicate that water levels in both ponds declined gradually during early spring when the weather was abnormally dry. In mid-June, both ponds began to rise in response to a period of increased rainfall. The pond hydrographs show recurrent episodes of rapid rise followed by gradual drawdown due to individual rain events and intervening periods of dryout.

Evaporation from the ponds proceeded at a relatively constant rate until late autumn when it began to level out (Figs. 6C & 6G). In contrast to evaporation and precipitation, the seepage terms varied both in magnitude and direction over short time-scales (Fig. 6D & 6H). Depicted graphically as cumulative seepage, there was net flow from the peatland to the pond during time periods when the seepage term is rising, (i.e. the pond stage has risen more than the difference between P and E). When the seepage term is falling, this flow path is reversed and there was net flow from the pond to the peatland. As seen more clearly when the seepage term is plotted on an expanded scale, there were frequent reversals in the inferred direction of flow across the riparian boundary; and the reversals were usually of short duration (Fig $6D_1$ & $6H_1$). As a result, cumulative seepage was a small negative term in the water budgets when integrated over the entire ice-free season.

In general, the highly resolved water budgets indicate that peatland porewaters pulsed towards the ponds during some rain events. Then, during intervening periods of dry weather, flow was dominated by gradual outseepage from the ponds toward the peatlands. Unfortunately, the absolute magnitude of subsurface influx and outflux cannot be inferred from net seepage values alone. However, the hydrographs for near-shore peatland wells argue against large and sustained rates of subsurface flow-through (Fig. 4).

Citizen Science. In Vilas County concern about record low lake levels in 2008 spurred local citizens and lake associations to form a lake level monitoring network comprised of citizen scientists. The network is administered by the North Lakeland Discovery Center (NLDC, a local NGO) and is supported by a grant from the Citizen Science Monitoring Program of the Wisconsin Department of Natural Resources (WDNR) and by the Wisconsin Focus on Energy EERD program. With technical guidance from limnologists at neighboring UW-Madison Trout Lake Research Station, citizen scientists have installed geographic benchmarks and staff gauges on 26 area lakes. The project engages citizen and student science participants including homeowners, non-profit organization member-participants, and local schools. Each spring, staff gauges are installed and referenced to fixed benchmarks after ice-off by NLDC and dedicated volunteers. Volunteers read and record staff gauges on a weekly basis during the ice-free season; and maintain log books recording lake levels to the nearest 0.5 cm. At the end of the season, before ice on, gauges are removed and log books are collected by the NLDC coordinator.

This program is the first of its kind in Wisconsin to utilize citizen scientists to collect lake level data. The retention rate for volunteers has been 100% over the four years since inception, and the program expanded from four lakes in 2008 to twenty-six lakes in 2011. NLDC stresses the importance of long-term monitoring and the commitment that such monitoring takes. The volunteers recognize this importance and have fulfilled their monitoring commitments on an annual basis. All participating volunteers receive a summary report at the end of the year, and, if requested, a graph that is updated monthly. Recruitment has been through lake associations, town boards, word of mouth, newspaper articles, community events, and the NLDC citizen science webpage. Local interest and participation are high, perhaps due to the value that citizens place on lakes and the concern that they have about declining water levels.

Future plans call for data to be compiled and submitted to a database management system, coordinated within the Wisconsin Surface Water Integrated Monitoring System (SWIMS), a statewide information system managed by the WDNR in Madison. NLDC will be collaborating with the SWIMS database manager to develop data entry screens based on records collected by citizen scientists.

Webpage.

The project webpage can be found at: http://www.wetlands.gleon.org

Technical Reports and Presentations.

Watras, Carl, Paul Hanson, Mike Morrow and Yu Hen Hu. 2009. Potential effects of climate on fluxes of carbon and water in northern Wisconsin lakes. FOE Seminar, June 2009, Madison, WI.

Watras, CJ, PC Hanson, TL Stacy, KM Morrison, J. Mather, Y-H Hu and P Milewski. 2011. A temperature compensation method for CDOM fluorescence sensors in freshwater. Limnology and Oceanography_Methods 9: 296-301.

Kretschmann, A., A. Drum, J. Rubsam, C.J. Watras, A. Cellar-Rossler. 2011. A Citizen Science Program for Monitoring Lake Stages in Northern Wisconsin. Annual meeting of the American Geophysical Union, December, 2011, San Fransisco, CA.

Watras, C.J. 2012. Low-power wireless sensor networks for monitoring lakes and watersheds. North American Lake Management Society, 32nd International Symposium. November 7-9, 2012, Madison, WI

Watras, Carl J., Paul C Hanson , Michael Morrow, Ken Morrison, Sean Scannell, Steve Yaziciaglu, Jordan S Read and Yu-Hen Hu. 2012. Wetland observatories: monitoring the impact of weather and climate on hydrochemical dynamics with wireless sensor networks (WSNs). (submitted)

References.

Buffam, I., Carpenter, S.R., Yeck, W., Hanson, P.C. and Turner, M.G., 2010. Filling holes in regional carbon budgets: Predicting peat depth in a north temperate lake district. J. Geophys. Res., 115 (G3, G01005, doi:10.1029/2009JG001034).

Buffam, I. et al., 2011. Integrating aquatic and terrestrial components to construct a complete carbon budget for a north temperate lake district. Global Change Biology, 17: 193-1211.

Cardille, J.A. et al., 2007. Carbon and water cycling in lake-rich landscapes: Landscape connections, lake hydrology, and biogeochemistry. J. Geophys. Res., 112: 1-18.

Dorrepaal, E. et al., 2009. Carbon respiration from subsurface peat accelerated by climate warming in the subarctic. Nature, 460: 616-619.

Evans, C.D., Chapman, P.J., Clark, J.M., Monteith, D.T. and Cresser, M.S., 2006. Alternative explanations for rising dissolved organic carbom export from organic soils. Global Change Biology, 12: 2044*2053.

Gerla, P.J., 1992. The relationship of water table changes to the capillary fringe, evapotranspiration, and precipitation in intermittent wetlands. Wetlands, 12: 91-98.

Hemond, H.F., (1980). *Biogeochemistry of Thoreau's Bog, Concord, Massachusetts.* Ecological Monographs. 50 (4): 507-526.

Holden, J. and T.P. Burt, (2003). *Hydrological Studies on Blanket Peat: The Significance of the Acrotelm-Catotelm Model.* Journal of Ecology. 91 (1): 86-102.

Ingram, H.A.P., (1982). *Size and shape in raised mire ecosystems: a geophysical model.* Nature. 297: 300-303.

Ise, T., Dunn, A.L., Wofsy, S.C. and Moorcroft, P.R., 2008. High sensitivity of peat decomposition to climate change through water-table feedback. Nature Geoscience, 1: 763-766.

Johnson, W.C., Boettcher, S.E., Poiani, K.A. and Guntersperge, G., 2004. Influence of weather extremes on the water levels of glaciated prairie wetlands. Wetlands, 24(2): 385-398.

Johnson, W.C. et al., 2005. Vulnerability of northern prairie wetlands to climate change. Bioscience, 55(10): 863-872.

Johnson, W.C. et al., 2010. Prairie wetland complexes as landscape functional units in a changing climate. Bioscience, 60(2): 128-140.

Kundzewicz, Z.W. et al., 2007. Freshwater resources and their management. Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson, Eds., Cambridge University Press, Cambridge, UK, 173-210.

Loheide, S.P., II, 2008. A method for estimating subdaily evapotranspiration of shallow groundwater using diurnal water table fluctuations. Ecohydrology, 1: 59-66.

Loheide, S.P., II, Butler, J.J., Jr. and Gorelick, S.M., 2005. Estimation of groundwater consumption by phreatophytes using diurnal water table fluctuations: A saturated-unsaturated flow assessment. Water Resources Research, 41(W07030): doi:10.1029/2005WR003942.

Mackay, D.S., Ewers, B.E., Cook, B.D. and Davis, K.J., 2007. Environmental drivers of evapotranspiration in a shrub wetland and an upland forest in northern Wisconsin. Water Resources Research, 43(W03442, doi:10.1029/2006WR005149).

Magnuson, J.J., Kratz, T.K. and Benson, B.J. (Editors), 2006. Long-term Dynamics of Lakes in the Landscape. Long-term Ecological Research Network Series. Oxford University Press, 400 pp.

Prairie, Y.T., P.A. del Giorgio, C. Roehm, and A. Tremblay, (2010). *Insights on riverine metabolism from continuous measurements of CDOM fluorescence in Eastmain-1 Reservoir, Quebec.* Verh. Internat. Verein. Limnol. 30 (10): 1545-1548.

Rosenberry, D.O. and Winter, T.C., 1997. Dynamics of water-table fluctuations in an upland between two prairie-pothole wetlnads in North dakota. Journal of Hydrology, 191: 266-289.

Sandford, RC, R. Bolb and PJ Worsfolda. 2010 In situ determination of dissolved organic carbon in freshwaters using a reagentless UV sensor. J. Environ. Monit., 12: 1678–1683. DOI: 10.1039/c0em00060d

Spencer, R.G.M., B.A. Pellerin, B.A. Bergamaschi, B.D. Downing, T.E.C. Kraus, et al., (2007). *Diurnal variability in riverine dissolved organic matter composition determined by in situ optical measurement in the San Joaquin River (California, USA).* Hydrological Processes. 21: 3181-3189.

Watras, C.J. et al., 2011. A temperature compensation method for CDOM fluorescence sensors in freshwater. Limnology and Oceanography_Methods 9: 296-301.

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

White, W.N., 1932. A method of estimating ground-water supplies based on the discharge by plants and evaporation from soils: Results of investigations in Escalante Valley, Utah. 659-A, U.S. Geol. Surv. Water Supply Paper.

WICCI, 2011. Wisconsin's Changing Climate: Impacts and Adaptation. Wisconsin Initiative on Climate Change Impacts., Nelson Institute for Environmental Studies, University of Wisconsin-Madison and the Wisconsin Department of Natural Resources, Madison, WI.