Transient Functioning of a Groundwater Wetland Complex, Allequash Basin, Wisconsin

WR05R007

Final Report
to the
Water Resources Institute
University of Wisconsin

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PROJECT SUMMARY

Title: Transient Functioning of a Groundwater Wetland Complex, Allequash Basin, Wisconsin

Project ID: WR05R007

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Background/Need: The location of wetlands in the transition zone between terrestrial and aquatic ecosystems and the associated cycling of wet and dry periods creates a unique and ecologically/environmentally important hydrological environment. Wetlands are important for fostering nutrient transformation, floodwater retention, and as areas of groundwater recharge/discharge. However, there are few studies that focus on identifying processes that control the flow of groundwater in peat dominated wetlands. Identification of processes that control flux, flow paths and residence times of groundwater are critical in quantifying chemical and biological cycles within wetland ecosystems.

Objectives: The objective of the research was to identify controls on groundwater flux, flow directions and residence time of water within a fen/stream complex within the Allequash basin in Vilas County, northern Wisconsin, using fine scale spatial and temporal field measurements in combination with a calibrated groundwater flow and heat transport model.

Methods: Field measurements of water levels, groundwater temperature, stream discharge, precipitation and air temperature were monitored over a two year period within the wetland. Fine scale spatial and temporal temperature measurements were made within the streambed of Allequash Creek in order to identify zones of groundwater discharge. Ground penetrating radar was used to map the extent of peat within the wetland in order to identify possible hydrostratigraphic controls on groundwater discharge. Field measurements were incorporated into a three-dimensional groundwater flow model, which was calibrated with the aid of a heat transport model, to identify groundwater flow paths and residence times within the wetland.

Results and Discussion:

Results from the two-year monitoring of water levels showed very little temporal fluctuation in water levels with maximum fluctuations on the order of 15 centimeters. There are, however, pronounced spatial patterns. Fine scale temperature measurements, which were taken along the streambed in Allequash Creek using a distributed temperature sensor (DTS), were used to identify zones of focused groundwater discharge. Spatial patterns were evident in the geology as well. Results from the geophysical surveys showed the depth to bedrock and the extent of peat within the wetland. Ground penetrating radar (GPR) surveys identified a strong reflector at depth, which correlated with the interface between peat and underlying sand and gravel in peat cores. GPR results also showed a correlation between breaks in slope in the peat/sand and gravel interface and springs and spring fed ponds in the wetland.

Results from the groundwater flow model showed that water of short residence times within the peat, on the order of 50 days, discharged in zones of focused groundwater discharge identified with the DTS. These zones were also located next to a break in slope identified using GPR. Longer flow paths discharging to the stream along diffuse discharge zones have residence times within the peat greater than 100 days.

Conclusions/Implications/Recommendations:

Spatial variability is more important than temporal variability in this wetland, which is likely to be the case for other wetlands in northern Wisconsin. Hence, in the future, monitoring systems should be designed to capture spatial variability; observation wells should be installed uniformly throughout the wetland rather than concentrated into transects. Diurnal fluctuations in water levels were caused by evapotranspiration and were on the order of 4 centimeters. Annual fluctuations were on the order of 15 centimeters. Seasonal monitoring of water levels is adequate to capture major temporal trends.

A break in slope in the peat/sand and gravel interface is correlated with the location of ponds and springs in the Allequash wetland. Similar ponds are present in other peat-dominated wetlands within Vilas County where breaks in slope between the peat/sand and gravel interface may also be present.

Fine scale spatial and temporal measurements along the streambed of Allequash Creek show focused zones of groundwater discharge. These zones correlate with groundwater of short residence times within the peat and may be "hot spots" for geochemical and biological reactions within the wetland.

Related Publications:

Lowry, C., J. F. Walker, R. J. Hunt, and M. P. Anderson (2007), Identifying spatial variability of groundwater discharge in a wetland stream using a distributed temperature sensor, Water Resour. Res., doi:10.1029/2007WR006145, in press.

Lowry, C.S., Walker, J.F., Hunt, R.J., and Anderson, M.P., 2007. Evidence for Focused Groundwater/Surface water Interaction Using a Distributed Temperature Sensor (abstract), in The Future of Wisconsin's Water Resources: Science and Policy: Wisconsin Dells, WI, Wisconsin Section of the American Water Resources Association, p. 13 Award: Best Student Paper.

Lowry, C.S., Walker, J.F., Hunt, R.J., Fratta, D., and Anderson, M.P., 2007. Geophysical and temperature characterization of groundwater/surface water interactions in a peat-dominated wetland (abstract), in Ground Water as a Catalyst for Change: Wisconsin Dells, WI, Wisconsin Ground Water Association, p. 5 Award: Best Graduate Student Paper.

Lowry, C.S., Anderson, M.P., and Hunt, R.J., 2006, Modeling groundwater flow and heat transport within a fen/stream complex, p. 278-282 in MODFLOW and More 2006 - Managing Ground Water Systems: Proceedings of the 7th International Conference of the International Ground Water Modeling Center. Golden, CO: Colorado School of Mines.

Lowry, C. S., Anderson, M. P., Hunt, R. J., and Walker, J. F., 2006, Toward Better Simulations of Wetland Hydrology- the Need for Diverse Field Data Collection, (abstract), *in* Wisconsin's Water Resources: Conflicts and Collaborations: Elkhart Lake, WI, Wisconsin Section of the American Water Resources Association, p. 35

Key Words: Peat wetlands, Groundwater/Surface water interactions, Temperature, Groundwater flow and heat transport modeling, Distributed temperature sensor, Ground penetrating radar

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INTRODUCTION

Allequash Wetland is a peat dominated wetland/stream complex located in the Trout Lake basin in northern Wisconsin (Figure 1). The wetland is situated within low-relief glacial terrain, which consists of 30 to 50 m of outwash sand and gravel overlying crystalline bedrock. The wetland covers an areal extent of 32 hectares, which is comprised predominately of peat of varying thickness. Research presented here focuses on the western lobe of the wetland complex (Figure 1). The layer of glacial outwash creates a highly conductive unit that promotes groundwater discharge to Allequash Creek. Precipitation within the Trout Lake basin averages around 79 cm per year and recharge to the water table is approximately 27 cm per year (Pint et al. 2003; Walker et al. 2003).

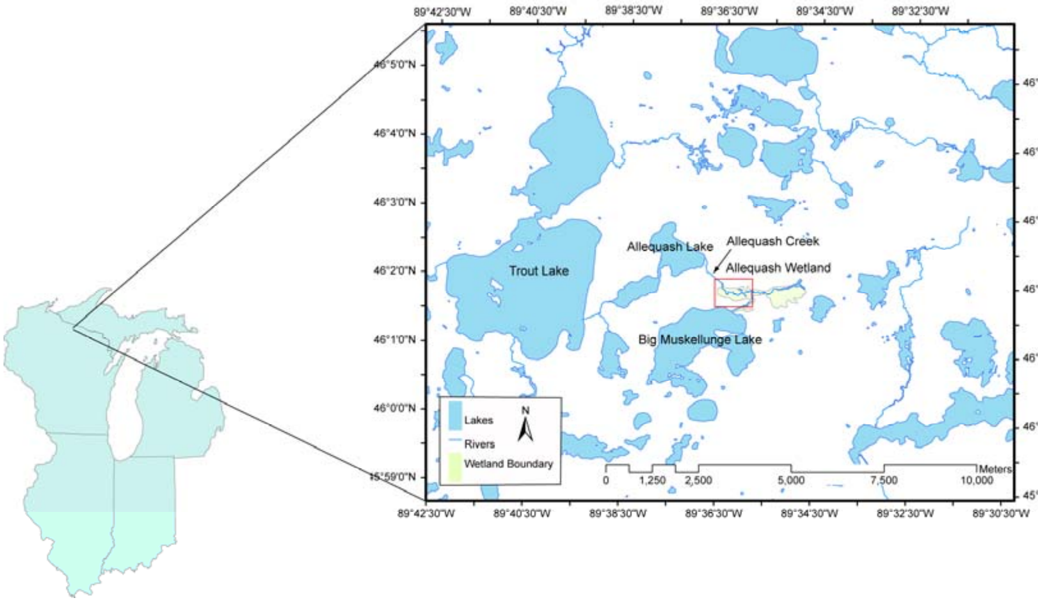

Figure 1. Location of Allequash Wetland within the Trout Lake basin in Northern Wisconsin.

Allequash wetland is within the National Science Foundation's North Temperate Lakes Long-Term Ecological Research (NTL-LTER) site and the U.S. Geological Survey's Trout Lake Water, Energy and Biogeochemical Budgets site. Prior work on the regional hydrogeology of the basin includes both field studies and groundwater modeling (e.g., Hunt et al. 2006a; Hunt et al. 2006b; Dripps et al. 2006; Dripps, 2003; Pint et al. 2003; Kim et al. 2000; Krabbenhoft et al. 1995 and 1992; Kenoyer et al. 1989). The existing monitoring network in the basin includes 60 observation wells, 4 stream gauging stations, several soil pits, and a variety of data related to surface water and groundwater chemistry. However, the wetland study site, which is the focus of this research, has had minimal previous study.

Previous and on-going work along Allequash Creek includes investigations of isotope geochemistry, carbon sources, mercury cycling, regional groundwater flow paths and the impact of groundwater surface water interactions on ecological systems. Isotope analyses show distinct source water differences (terrestrial, lake and wetland) along Allequash Creek in both surface and groundwater samples (Walker et al. 2003; Masbruch 2005). Simulations of regional groundwater flow paths support the isotope results and show that flow paths discharge into Allequash Creek from both lake and terrestrial sources (Pint et al. 2003). Recharge within the basin is dependent on land cover and timing of precipitation events; recharge has been quantified both spatially and temporally using field methods and numerical models (Dripps et al. 2006; Dripps 2003). Sources of dissolved organic carbon within the stream are associated with peat and peatland vegetation (Elder et al. 2000). Seasonal variations in concentrations of both dissolved organic carbon and mercury within Allequash Creek have been observed (Krabbenhoft et al. 1995). Elevated concentrations of methylmercury have been detected within upwelling zones in hyporheic zones as compared to open water portions of Allequash Creek (Meyer 2004). Variations in the richness of benthic communities is associated with high groundwater discharge along Allequash Creek as compared to other streams within the basin classified as weak groundwater discharge and groundwater recharge streams (Hunt et al. 2006b). Calculations of groundwater flux to Allequash Creek based on temperature gradients show that groundwater discharge increases downstream (Spitzer-List 2003).

In this study, a combination of field measurements and computer simulations were used to quantify groundwater flux, flow directions and residence time of water within the wetland. Residence times and flow paths through the peat are important parameters for future work relating to geochemical interactions between groundwater and the peat matrix.

PROCEDURES AND METHODS

Groundwater levels and temperature were monitored over a two year period from May 2005 to September 2007 in twelve nests of monitoring wells installed in two transects (Figure 2). Each transect contained a nest of four monitoring wells at six locations evenly distributed on each side of the stream. Nests consist of wells screened at the water table, and at 3 meters, 6 meters and 8 meters below the water table. Screen depths were based on results from a geophysical survey using ground penetrating radar (GPR) so that wells were placed at the top, middle and bottom of the peat in addition to one well just below the peat/sand and gravel interface. Based on the location of these wells slug tests were performed to estimate hydraulic conductivity of the peat and sand units. Continuous water level measurements were taken in the water table wells over the two year study period in addition to manual measurements taken monthly in all wells. Groundwater temperatures were monitored using thermocouples in selected well nests.

Geophysical surveys using ground penetrating radar (GPR) (Figure 2), as well as resistivity and seismic surveys were conducted to identify the depth to bedrock and to delineate the boundary between peat and underlying sand and gravel. GPR surveys were run using both 25 and 50 MHz antennas based on the thickness of peat. Reducing the frequency of the system allows for better depth of penetration; however, reducing the frequency increases the wavelength of the signal thus reducing the resolution of the system.

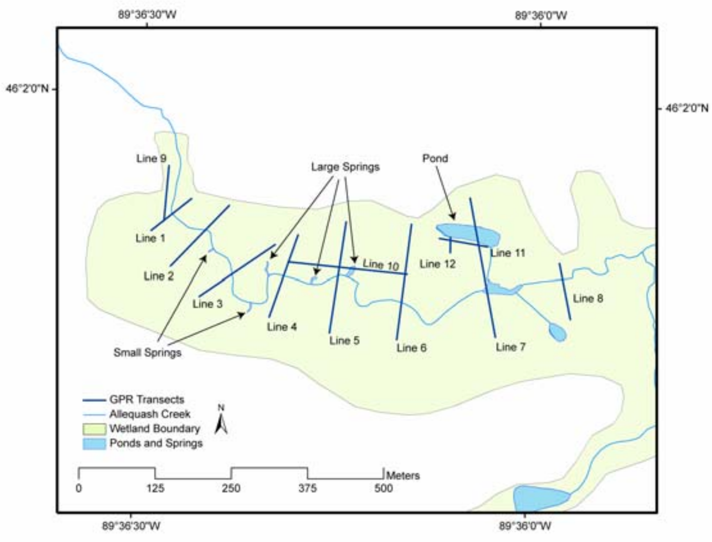

Figure 2. GPR transects and locations of surface water features (modified from Lowry et al. in preparation). Monitoring wells were installed along lines 2 and 7.

A survey of streambed temperatures using a distributed temperature sensor (DTS) in Allequash Creek (Figure 3) was performed during September-October 2006 to identify zones of groundwater discharge. The DTS system is a fiber optic based temperature sensor, which can measure changes in temperature every 60 seconds at 1 meter resolution along a length of over 800 meters of the stream (Figure 3). The

DTS sends laser light down a fiber optic cable placed just below the sediment/water interface where changes in temperature along the cable cause backscatter. Temperature changes along the length of the cable can then be calculated based on the intensity of the backscattered light. It is possible to determine zones of groundwater discharge from temperature measurements in this wetland because groundwater is a relatively cool and constant temperature between 6 to 7 degrees C whereas surface water is several degrees warmer, with a temperature range of 12 to 20 deg C.

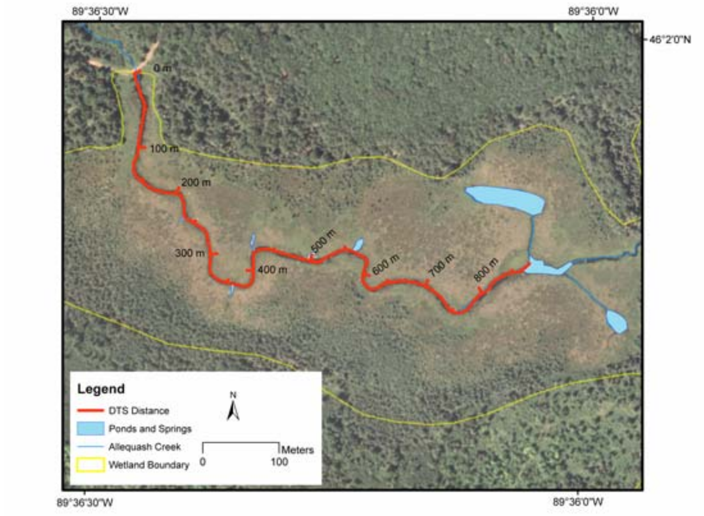

Figure 3. Location of the fiber optic based distributed temperature sensor along Allequash Creek. Allequash Creek Flows from east to west.

A coupled three-dimensional, transient groundwater flow and heat transport model was created for Allequash Wetland using the computer code SEAWAT (Langevin et al. 2003). Boundary conditions for the wetland model were taken from an existing regional model of the Trout Lake basin (John 2006). The wetland model was discretized into 5 meter by 5 meter grids with 19 layers ranging in thickness from 1 meter within the peat to 5 meters within the underlying sand and gravel (Figure 4). The parameter estimation code PEST (Doherty 2004) was used to calibrate the groundwater flow and heat transport model. Based on the GPR survey, three zones were identified consisting of peat, sand, and a transitional zone between peat and sand (Figure 4). Pilot points (Hunt et al. 2007, deMarsily et al. 1984) were used to estimate the distribution of hydraulic conductivity within these zones in order to identify heterogeneity within zones during calibration. Particle tracking was then used with the calibrated groundwater flow and heat transport model to determine groundwater flow paths and residence times within the wetland. Particles were place within

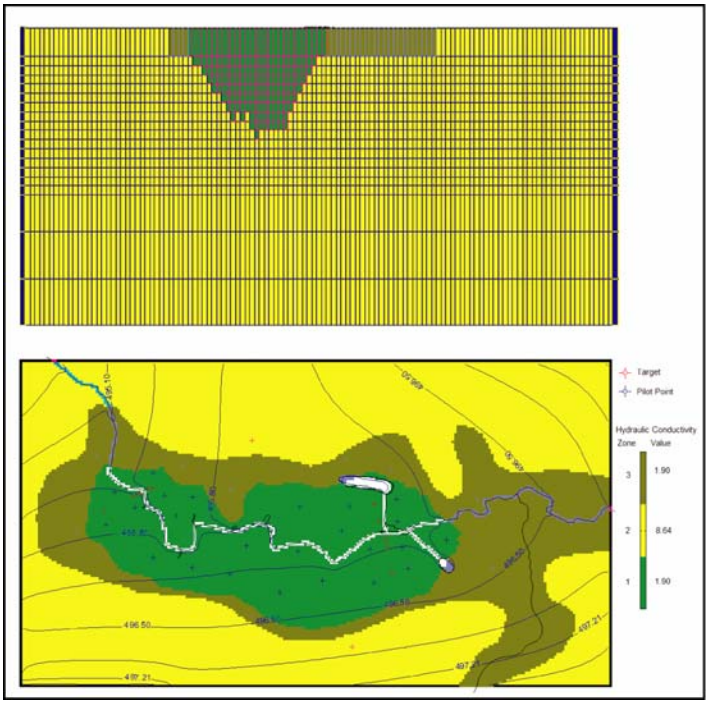

Figure 4. Initial hydrostratigraphic units used in the groundwater flow model. Zones were assigned based on the GPR survey representing peat (green), sand (yellow) and a transitional zone (brown). Monitoring wells (targets) are shown by red crosses and pilot points are shown by blue crosses.

model cells representing Allequash Creek and particles were traced backward through time to determine flow paths of groundwater discharging into Allequash Creek.

RESULTS AND DISCUSSION

Water levels within Allequash Wetland were relatively stable over the two year monitoring period. Fluctuations within the water table wells were on the order of 15 centimeters in response to fluctuations in precipitation and evapotranspiration (ET). Water levels in deeper wells placed at depths of 3 and 6 meters showed less variation with fluctuations on the order of 5 to 10 centimeters. Diurnal fluctuations in the water table wells were around 4 centimeters and were caused by a decline during the day due to ET followed by recovery at night. Hydrographs of all wells may be found in Lowry (in preparation). The daily water level cycles were used to calculate the amount of water removed from the system by ET between precipitation events using the method of White (1932); ET rates average 7.32 x 10^{-3} m/day. During and shortly after precipitation events it was not possible to calculate ET because recharging water masked the daily signals.

Geophysical results show depth to bedrock within the wetland is on the order of 30 meters. These results are within the range of previous measurements taken within the Trout Lake basin (Okqueze 1983). The GPR survey identified a strong reflector at depth and peat cores identified the reflector as the interface between peat and the underlying sand and gravel (Figure 5). Peat within the wetland varies to a maximum depth of over 16 meters. Peat cores identified a change in lithology within the peat from an upper black unit with fibers and wood debris to an underlying homogenous green unit (Figure 5, core 1). Lab results show an increase in both the gravimetric water content and electrical conductivity of the lower green unit (Lowry et al. in preparation). Unfortunately the resolution of the GPR system is not able to identify the change from the upper black peat to the lower green unit even though the contrast in electrical conductivity exists. Based on slug tests within the wetland, the lower green unit appears to have a much lower hydraulic conductivity; however, the extent of this unit has only been identified in peat cores.

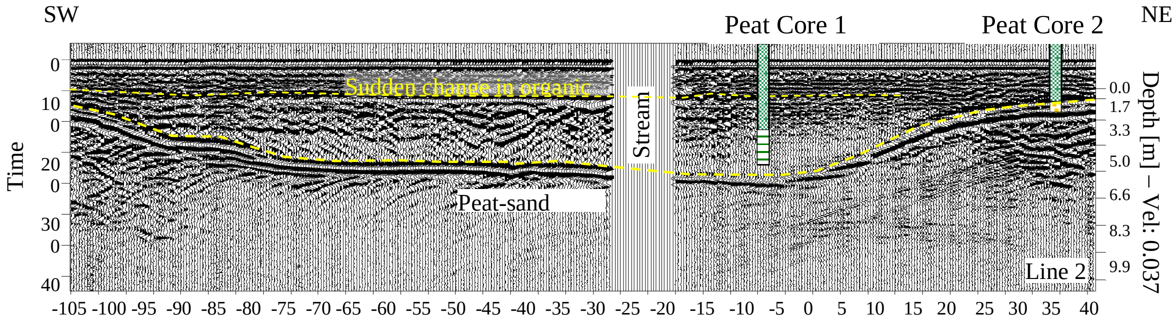

Figure 5. Results from GPR line 2. The interface between peat and the underlying sand and gravel is shown. Peat cores show locations where soil samples were taken to verify the GPR survey results. Core 1 is located 22 meters from the stream and shows a change in lithology from black peat to an underlying green unit. Core 2 is located 75 meters from the stream and shows an upper black peat unit with a sharp transition to clean sand at a depth of 1.8 meters (Modified from Lowry et al., in preparation).

By interpolating between GPR transects, a three-dimensional representation of the extent of peat was constructed (Figure 6A). Results show an increase in thickness of peat from west to east with the peat forming a basin that appears to be independent of the location of Allequash Creek (Figure 6B). A comparison between the changes in the thickness of peat and location of surface water features shows a correlation between breaks in slope in the peat/sand and gravel interface and the location of ponds and large spring complexes (Figure 6B). The large pond on the north side of the wetland and the three large spring complexes (Figure 2) are positioned directly above sharp changes in the peat/sand and gravel interface (Figure 6). The change in the slope of the interface together with the hydraulic conductivity contrast between peat and the underlying sand and gravel causes conditions optimal for refraction of flow lines. Based on the position of these features it is likely that groundwater flowing horizontally through the sand and gravel intercepts the interfaces with the overlying peat causing the flow lines to refract (Figure 7) and intersect the land surface creating a pond or spring complex.

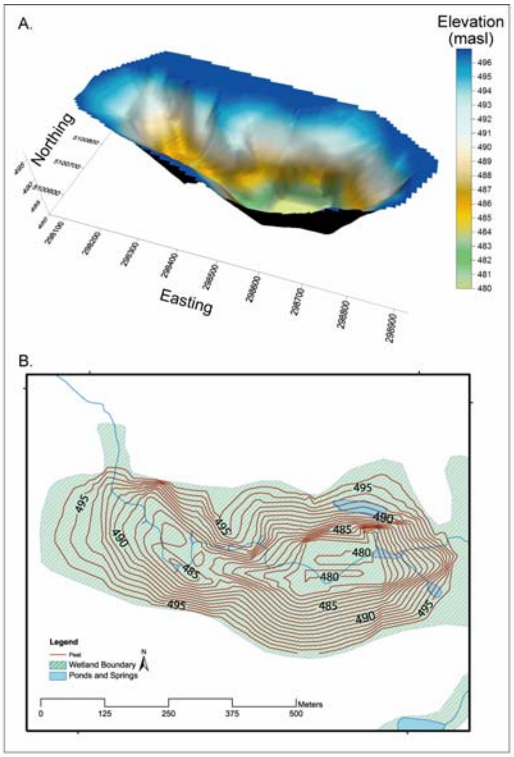

Figure 6. Depth to peat/sand and gravel interface within Allequash Wetland. A) Three-dimensional basin structure representing the extent of peat. B) Contour plot showing the relation between breaks in slope in the peat/sand and gravel interface and ponds/large spring complexes. Contours show the elevation (masl) of the peat/sand and gravel interface at 1 meter intervals.

Results from the Distributed Temperature Sensor (DTS) show cool temperatures within the large pond (at lengths 900 to 1300 meters, Figure 3) and several temperature anomalies at 450, 500, and 600 meters along the length of the streambed (Figure 8). The cooler temperatures within the pond fit well with the conceptual model of refraction of flow paths causing discharge at the surface. Initially the fiber optic cable was placed along the length of the stream and into the large pond on the north side of the wetland (Figure 3). Unfortunately the cable was broken not long after installation at a distance of approximately 650 meters (Figure 3). Temporal changes in groundwater discharge identified as a result of the DTS survey show stable groundwater discharge zones through time (Figure 9). A comparison of streambed temperature over the measurement period shows constant cool temperature at several locations along the streambed (i.e. 150 m, 360 m, 450 m, Figure 9). An analysis of the standard deviation of temperature through time also demonstrates the locations of the zones of relatively constant temperature are stable (Figure 9). Zones of low standard deviation are controlled by a constant temperature source such as groundwater. During summer months solar heating of the streambed during the day and cooling at night causes a high standard deviation.

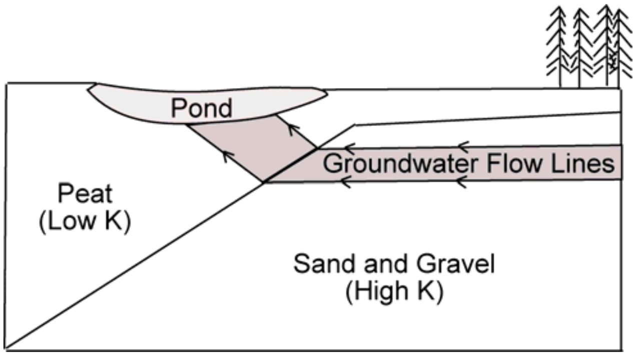

Figure 7. Refraction of flow lines from high conductivity (K) sand and gravel to low conductivity peat causing the formation of surface water features such as ponds and larger spring complexes.

Seepage meters were installed at zones of low standard deviation in temperature identified using Figure 9. Groundwater discharge was two orders of magnitude higher than in zones with high standard deviations (Lowry et al. 2007). Field observation during the winter confirm the locations of these zones of focused discharge; small open water pools form within the frozen stream surface at zones identified as having a low standard deviation in temperature.

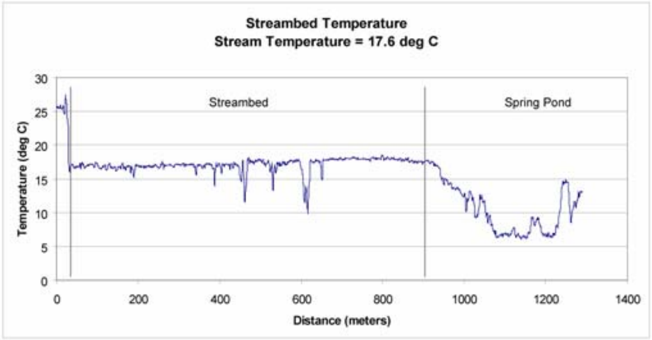

Figure 8. Streambed temperatures along Allequash Creek (Lowry et al. 2007). The position of the cable is shown on figure 3.

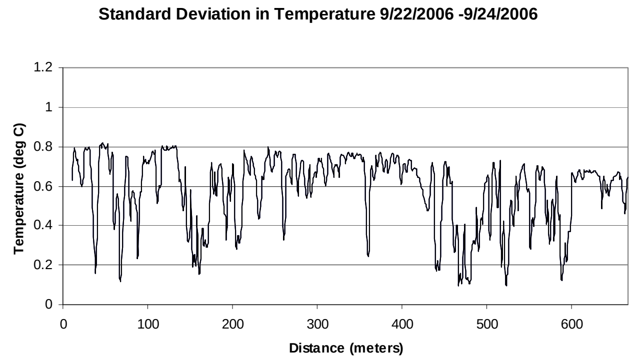

Figure 9. Standard deviation of streambed temperature over 48 hour measurement period (Modified from Lowry et al. 2007).

Results from the DTS work lead to a new conceptual model of groundwater/surface water interaction within a groundwater fed wetland where groundwater discharges to the stream in focused zones (Figure 9) in contrast with the traditional model that assumes continuous diffuse groundwater discharge over the streambed. Diffuse flow would result in a relatively smooth temperature profile along the length of the streambed. In the new conceptual model there are discrete zones of groundwater discharge in between zones of diffuse discharge (Figure 10). The reach from 40 to 400 meters contains distinct zones of groundwater discharge (Figure 10). From 400 m to 600 meters, zones of groundwater discharge appear to blend together typical of what might be observed in a traditional diffuse flow system; however, discrete zones of groundwater discharge can still be individually identified within the reach. A small losing section of the stream was identified from stream gaging at a location between 0 to 40 meters. The losing stretch is caused by water backed up by a culvert at the downstream end of the wetland (Figure 10).

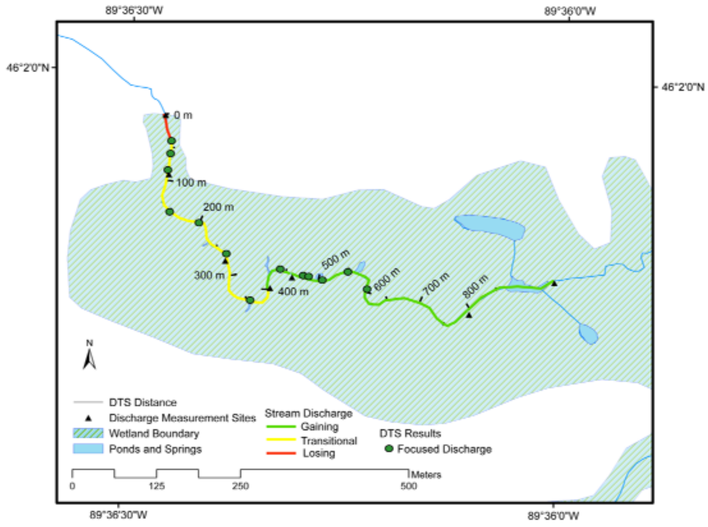

Figure 10. Conceptual model of groundwater discharge to Allequash Creek based on distributed temperature measurements (Lowry et al. 2007).

Calibration of the groundwater flow and heat transport model produced a variation in hydraulic conductivity in peat over two orders of magnitude.

Inclusion of this amount of heterogeneity was required in order to fit observations throughout the wetland. Additional details about the model and its calibration is in Lowry (in preparation).

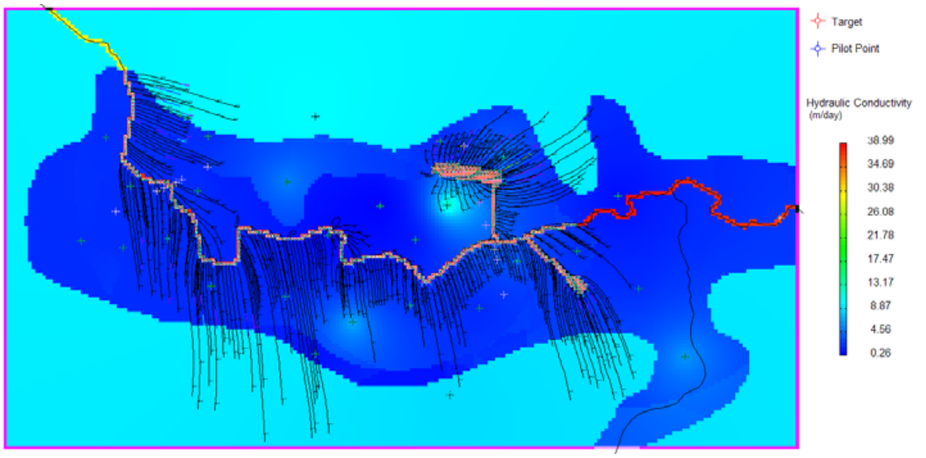

Figure 11. Particle flow paths based on the calibrated groundwater flow and heat transport model.

Particle tracking based on the calibrated flow model was performed for the period May 2005 to June 2007 (Figure 11) in order to track the movement of water through the peat. We focus on the peat since peat within Allequash wetland is thought to be a local source of dissolved organic carbon, which discharges to the stream (Elder et al. 2000). A total of 379 particles were distributed along the stream and then tracked backwards through time using the code MODPATH (Pollock 1994). Of these, 91 particles quickly moved out of the peat and into the underlying sand and gravel resulting in a residence time within the peat of less than 3 days. The remaining 288 particles stayed in the peat for a longer period of time before entering the sand. These particles had an average residence time of 134 days within the peat. The minimum residence time of the 288 particles in the peat was 3 days and the maximum residence time in the peat was 791 days.

At the end of the simulation 98% of the particles were within the sand and gravel but none of the particles exited the model during the 791 day simulation period, which indicates that all of the groundwater discharging to Allequash Creek comes from outside the wetland; none is recharged locally within the wetland. Most of the groundwater that discharges to the stream enters from the south side of the wetland following the regional flow of groundwater flowing northward from Big Muskellunge Lake to Trout Lake (Figure 1). Pint et al. (2003) showed that the travel time from Big Muskellunge Lake to Allequash Creek is on the order of 10 years. Flow paths of groundwater discharging to Allequash Creek were relatively stable through time and showed no temporal trends over the simulation period.

Starting positions for those particles with short residence times (fewer than 50 days) correlate with zones of focused groundwater discharged identified with the DTS. Specifically, the section of Allequash Creek from 400-600 meters (Figure 3 and 8), which was identified as dominated by focused groundwater discharge, correlates with particles with low residence times within the peat (Figure 12). The reach between 400-600 meters also correlates with a break in slope between the peat and underlying sand and gravel unit (Figure 6b). Along the stream from 0-150 meters (Figure 3) the peat layer is very thin causing the particles to travel within the sand and gravel, which results in residence times of fewer than 3 days (Figure 12). At distances greater than 600 meters, residence times are at a maximum (Figure 12), which should be expected because the peat unit is thickest along this section of the stream (Figure 6b).

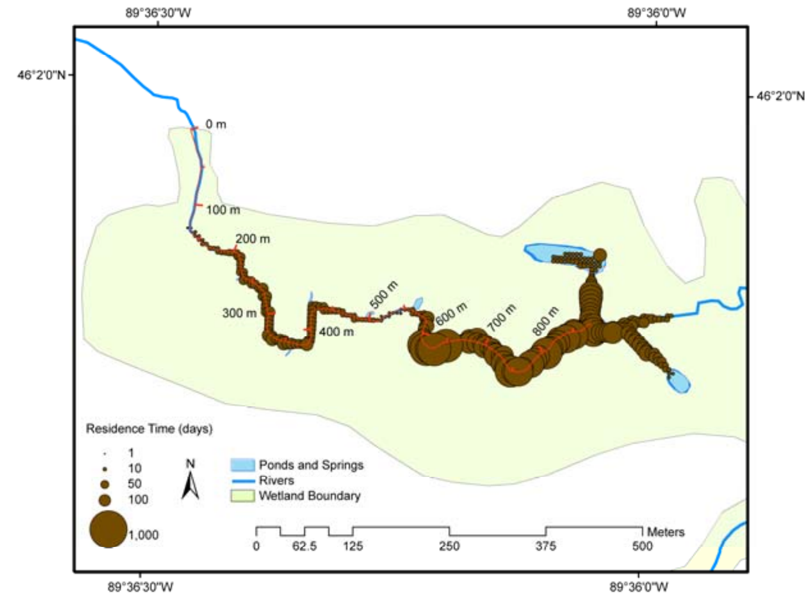

Figure 12. Residence time of groundwater discharging to Allequash Creek. The larger the brown circle the longer the residence time of discharging groundwater.

CONCLUSIONS AND RECOMMENDATIONS

Wetlands are important environments for nutrient transformation, floodwater retention, animal habitats and groundwater recharge/discharge. Identifying processes that control groundwater discharge is important to wetland dynamics including chemical cycling and the protection of habitats for wetland plants and animals.

Spatial variability is more important than temporal variability in this wetland, which is likely to be the case for other wetlands in northern Wisconsin. Hence, in the future, monitoring systems should be designed to capture spatial variability; observation wells should be installed uniformly throughout the wetland rather than concentrated into transects. Diurnal fluctuations in water levels were around 4 centimeters and are caused by evapotranspiration. Annual fluctuations were on the order of 15 centimeters. Seasonal monitoring of water levels is adequate to capture major temporal trends.

Geophysical surveys show that Allequash wetland appears to lie within an old lake basin (Figure 6). Results from the GPR survey show a correlation between the interface between peat and the underlying sand and gravel and the location of spring ponds and spring complexes. Breaks in slope between the peat/sand and gravel interface were observed below the large pond on the north side of the wetland and large spring complexes along the stream. These breaks in slope likely cause refraction of groundwater flow lines (Figure 7), which create ponds and springs at the land surface. Elongated ponds similar to the one located on the north side of the Allequash wetland have been identified at Spring Meadow Creek wetland, North Creek wetland and Ross Lake wetland, all in Vilas County. Wetlands throughout Vilas County were likely formed under similar conditions as Allequash wetland and are influenced by similar processes control groundwater flow.

Fine scale spatial and temporal temperature measurements along Allequash Creek using the distributed temperature sensor identified zones of focused groundwater discharge (Figure 10), which have two orders of magnitude higher discharge compared to background measurements in diffuse discharge zones. The results of this study identified a new conceptual model of groundwater discharge to a wetland stream in which focused zones of groundwater discharge play a controlling role in contrast to the traditional model of uniform diffuse discharge. Focused zones of groundwater discharge may be caused by soil pipes within the peat, which control subsurface water routing in blanket peatlands (Holden 2004 and 2005). These zones may be “hot spots” for geochemical and biological reactions within the wetland. Focusing of groundwater flow into focused discharge zones along the streambed decreases the residence time of groundwater within the peat, which has implications for carbon cycling and other geochemical interactions.

Results from a groundwater flow model of the wetland show that all of the groundwater discharging to Allequash Creek comes from outside the wetland; none is recharged locally within the wetland. The average residence time of groundwater within the peat is 135 days with a minimum travel time of 3 days. None of the particles exited the model during the simulation period of 791 days. Flow paths indicate that most of the water that discharges to Allequash Creek originates in the vicinity of Big Muskellunge Lake.

Recommendations for future work include fine scale chemical sampling along Allequash Creek. Focused zones of groundwater discharge create a short circuit for groundwater discharge to the stream and therefore changes in the chemistry of focused discharge water is likely very different from diffuse discharge water moving through the peat matrix. Some fine scale variations in chemistry along streams cannot be explained by hyporheic exchange (Dent and Grimm 1999) and may be associated with zones of focused groundwater discharge.

Additional work is also needed to identify the depositional environments that existed within both Allequash wetland and other wetlands in northern Wisconsin. The cause of the change in lithology from the upper black peat unit to the lower green unit identified from peat cores is unknown. Understanding this change in lithology may lead to a better model for past climates within the region. Age dating of peat below the large spring complexes and pond on the north side of the wetland would help determine if these surface water features were created after the peat was deposited or if these discharge zones were present during peat deposition.

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Lowry, C.S., D. Fratta, and M.P. Anderson. in Preparation. Linking basin geometry to groundwater/surface water interactions in a peat dominated wetland using Ground Penetrating Radar. To be submitted to Ground Water.

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APPENDIX A: Awards, Publications, and Presentations

Lowry, C.S., in Preparation, expected August 2008. Controls on groundwater flow in a peat dominated wetland/stream complex, Allequash Wetland, Northern Wisconsin, University of Wisconsin-Madison, PhD Thesis.

Lowry, C.S., D. Fratta, and M.P. Anderson. in Preparation. Linking basin geometry to groundwater/surface water interactions in a peat dominated wetland using Ground Penetrating Radar. To be submitted to *Ground Water*.

Lowry, C.S, Walker, J. F., Hunt, R. J., and Anderson, M. P., 2007. Identifying spatial variability of groundwater discharge in a wetland stream using a distributed temperature sensor, *Water Resources Research*, doi:10.1029/2007WR006145.

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Lowry, C.S., Walker, J.F., Hunt, R.J., and Anderson, M.P., 2007. Evidence for Focused Groundwater/Surface water Interaction Using a Distributed Temperature Sensor (abstract), in The Future of Wisconsin's Water Resources: Science and Policy: Wisconsin Dells, WI, Wisconsin Section of the American Water Resources Association, p. 13 Award: Best Student Paper.

Lowry, C.S., Walker, J.F., Hunt, R.J., Fratta, D., and Anderson, M.P., 2007. Geophysical and temperature characterization of groundwater/surface water interactions in a peat-dominated wetland (abstract), in Ground Water as a Catalyst for Change: Wisconsin Dells, WI, Wisconsin Ground Water Association, p. 5 Award: Best Graduate Student Paper.

Lowry, C.S., Anderson, M.P., and Hunt, R.J., 2006, Modeling groundwater flow and heat transport within a fen/stream complex, p. 278-282 in MODFLOW and More 2006 - Managing Ground Water Systems: Proceedings of the 7th International Conference of the International Ground Water Modeling Center. Golden, CO: Colorado School of Mines.

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