Groundwater Research Report
WRXXRXXX

ANTHROPOGENICALLY DRIVEN CHANGES TO SHALLOW GROUNDWATER IN SOUTHEASTERN WISCONSIN AND ITS EFFECTS ON THE AQUIFER MICROBIAL COMMUNITIES

Tim Grundl
Ryan Newton
Natalie Gayner
Madeline J. Salo

YEAR

Project Number
WR07R005

A THERMAL REMOTE SENSING TOOL FOR MAPPING SPRING AND DIFFUSE GROUNDWATER DISCHARGE TO STREAMS

Steven P. Loheide II
Department of Civil and Environmental Engineering
University of Wisconsin-Madison

Richard S. Deitchman
Nelson Institute for Environmental Studies
University of Wisconsin-Madison

Administered by:
University of Wisconsin Water Resources Institute

Funded by:
State of Wisconsin Groundwater Research and Monitoring Program

2009

This project was also supported, in part, by General Purpose Revenue funds of the State of Wisconsin to the University of Wisconsin System for the performance of research on groundwater quality and quantity. Selection of projects was conducted on a competitive basis through a joint solicitation from the University and the Wisconsin Departments of Natural Resources; Agriculture, Trade and Consumer Protection; Commerce; and advice of the Wisconsin Groundwater Research Advisory Council and with the concurrence of the Wisconsin Groundwater Coordinating Council.

A thermal remote sensing tool for mapping spring and diffuse groundwater discharge to streams

WR07R005

Final Report
to the
Water Resources Institute
University of Wisconsin

P.I. Steven P. Loheide II
Department of Civil and Environmental Engineering
University of Wisconsin-Madison
loheide@wisc.edu

R.A. Richard S. Deitchman
Nelson Institute for Environmental Studies
University of Wisconsin-Madison
deitchman@lclark.edu

September 30, 2009

Table of Contents

References

List of Figures and Tables

Figure 1: Time-lapse thermal data collected at one stream bank: *A)* Thermal image showing two regions of interest (SAT – saturated zone, UNSAT – unsaturated zone). *B)* Standard deviation of the 24 hour time lapse data, which exhibits the lower thermal inertia of the unsaturated zone. *C)* Thermal images at two-hour intervals *D)* 24 hour average temperature history of two regions of interest (SAT and UNSAT) *E)* Vertical soil moisture profile (5 cm increments) from the stream to the top of the stream bank.

Figure 2: Winter thermal imagery showing correlation between hydraulic conductivity and imaged seepage intensity

Figure 3: Thermal imagery of spring flow into Lake Wingra, Madison, Wisconsin collected from a fixed-wing aircraft. The imagery was collected in November 2008, when the groundwater temperature is warmer than the surface

Figure 4: Thermal imagery collected from the UAV at the East Branch Pecatonica 2006 restoration site in July 2008. The straight, left-right trending feature in panel A is a road, which appears warm relative to its surroundings in the thermal image. The imagery was collected in the afternoon on a warm summer day.

Figure 5: A) Comparison of remotely sensed, in-stream, and simulated temperature on July 24, 2008 for the East Branch Pecatonica River. The profile moves downstream left to right (0 km is upstream, 10.47 km is downstream). B) Comparison of simulated (line) and measured (circles) stream temperature at the locations of the three in-stream data loggers.

Figure 6: Longitudinal profile of groundwater discharge to the East Branch Pecatonica River determined using stream temperature modeling to match remotely-sensed stream temperature profiles

Figure 7: Comparison of simulated cases at an upstream (2.75 km) and downstream (7.75 km) location to the maximum daily maximum curve (solid line) developed by Wehrly et al. (2007). The absolute difference between the base case and the change in stream flow cases is greater at the downstream location for all simulations. Only the +5°C, -30% stream flow case crosses the empirical threshold developed by Wehrly et al. (2007).

PROJECT SUMMARY

Title: A thermal remote sensing tool for mapping spring and diffuse groundwater discharge to streams
Project ID: WR07R005
Investigators: Steven P. Loheide II, Principal Investigator, Civil & Environmental Engineering, UW-Madison, Richard S. Deitchman Research Assistant, Nelson Institute for Enviro. Studies, UW-Madison
Period of Contract: July 1, 2007 – June 30, 2009

Background/Need: Science-based management is essential to developing sustainable use of Wisconsin's water resources. Wisconsin is progressive nationally in water resources policy; WI Act 310 (2003), a groundwater quantity protection law, is one of the first pieces of legislation to recognize the interaction of groundwater and surface water. However, surface water/groundwater interactions have a high degree of spatial variability with groundwater entering streams both as focused discharge from springs and diffuse seepage through the streambed/banks. Unfortunately, there are few available methods for mapping groundwater discharge to streams at either small or large scales, making administration of WI Act 310 difficult. Because the differing thermal signatures of groundwater and surfaces water, thermal remote sensing offers a potential method for addressing this data need.

Objectives: The purpose of this research is to investigate the use of thermal remote sensing for water resources science and policy in WI. The objectives of this project are to demonstrate that remote sensing may be used to: (1) map the water table position and groundwater discharge at the seepage face, (2) acquire ultra-high resolution imagery of stream temperature for mapping both springs and diffuse groundwater discharge to streams, (3) validate stream temperature models used to predict the suitability of a streams thermal regime for supporting fisheries, and (4) assist the State of Wisconsin in implementing WI Act 310 to promote sustainable use of groundwater and protect spring resources.

Methods: (1) Ground-based thermal imaging was employed in the UW-Arboretum as a new, transferable, non-invasive method that uses heat as a natural tracer to image spatially variable groundwater discharge. (2) Thermal imagery was collected from both unmanned aerial vehicles and a single-engine airplane to map springs and diffuse groundwater discharge to streams. (3) Airborne thermal remote sensing data was collected to validate a one-dimensional stream temperature model of the East Branch Pecatonica River to predict the thermal suitability of the stream for fisheries under future climates.

Results and Discussion: Ground-based thermal imaging of groundwater in the University of Wisconsin Arboretum provides methods to (1) map the water table position along seepage faces using thermal imagery, and (2) image both focused and diffuse groundwater discharge to the surface. The methods rely, respectively, on the facts that (a) groundwater saturated regions are more resistant to diurnal temperature fluctuations when compared with unsaturated regions (b) within the saturated zone, greater magnitude of groundwater discharge results in increased stability of the thermal regime. Time-lapse thermal imagery over a diurnal cycle demonstrated that peak air temperature, when the difference between air and groundwater temperature is greatest, is the optimal time to collect thermal imagery of groundwater. Hydraulic conductivity measurements from a falling-head permeameter, validated our data interpretation by revealing a correlation between remotely sensed seepage intensity and hydraulic conductivity.

Thermal imagery collected during this project demonstrated that both focused groundwater discharge from springs and diffuse groundwater seepage to streams could be identified because of the differences in thermal signatures of surface- and ground-waters. Flights at the East Branch Pecatonica indicated that the thermal resolution of stream temperature maps collected from UAVs can be three times greater than those collected from small airplanes restricted to higher flight altitudes. The data show that UAVs are a viable alternative to small airplanes and may be employed to study finer scale processes (e.g. smaller springs).

Thermal imagery collected at the East Branch Pecatonica River, was used to validate a stream temperature model forecasting potential changes in stream temperature as a consequence of climate change. The model simulates stream temperature with three air temperature/groundwater temperature increase scenarios (1, 3 and 5°C) and changes in stream flow (-30% baseflow and +30% baseflow). The simulations reveal that in the more extreme climate change scenarios, native brook trout and non-native brown trout populations may not tolerate the new thermal regime in most reaches of the stream. However, the combined thermal remote sensing and modeling methodology identified a sub-reach with higher groundwater discharge that would serve as a thermal refuge even under climate change scenarios.

Conclusions/Recommendations/Implications:

Ground-based thermal imaging in the UW Arboretum

- Ground-based thermal imaging at the UW Arboretum provides a new method to map water table position and image both focused and diffuse groundwater flux along the seepage face.
- The new methodology will assist groundwater modelers, water resource managers, and agricultural engineers in visualizing and monitoring heterogeneity of groundwater flow at discharge interfaces.

Thermal remote sensing for mapping groundwater discharge and stream temperature

- Thermal imagery collected using both UAVs and small aircraft successfully demonstrated the use of thermal remote sensing in stream temperature and groundwater discharge assessments.
- The ability of thermal remote sensing methods to map groundwater discharge may prove useful in the administration of 2003 WI Act 310.
- Because of greater maneuverability, UAVs can collect thermal imaging data that improve the resolution of groundwater discharge analysis relative to manned aircraft
- Without alteration of current FAA regulations of UAVs, the future implementation of unmanned systems in Wisconsin water management may be limited, particularly for private entities.

Modeling climate change impacts on stream temperature using thermal imagery

- Thermal remote sensing is highly valuable for stream temperature model validation and analyses of thermal heterogeneity.
- Longitudinal profiles of stream temperature increase our understanding of spatially variable groundwater inflow to streams. This may assist in the identification of thermal refugia for fish.
- Model simulations highlight the potential threats to WI fisheries; in the most extreme climate change scenarios, stream temperature may cross thermal tolerance thresholds by Wehlry et al. (2007).

Related Publications:

1) Deitchman, R.S., and S.P. Loheide II (2009), Characterization of groundwater flux using ground-based thermal remote sensing at the seepage face, American Water Resources Association – WI Section 2009 Annual Meeting, Stevens Point, WI. "Best Student Platform" award winner.
2) Deitchman, R.S, (2009), Thermal remote sensing of stream temperature and groundwater discharge: Applications to hydrogeology and water resources policy in the state of WI, M.S. Thesis, UW-Madison.
3) Deitchman, R. S., and S. P. Loheide II (2009), Ground-based thermal imaging of groundwater flow processes at the seepage face, Geophys. Res. Lett., 36, L14401, doi:10.1029/2009GL038103.
4) Deitchman, R.S. and S.P. Loheide II (In review), Impacts of climate change on stream temperature and fish habitat of a Driftless Area trout stream.
5) Loheide, II, S.P. (2009), Characterization of groundwater processes in riparian areas using thermal remote sensing, NovCare 2009, Leipzig Germany
6) Loheide, II, S.P., (2007), Thermal remote sensing detection of groundwater discharge to streams, Invited Presentation, Geological Society of America Annual Meeting, Denver

Keywords: groundwater-surface water interaction, springs, stream temperature, climate change, seepage

Funding: State of Wisconsin Groundwater Coordination Council through the University of Wisconsin Water Resources Institute. (UWS/USGS)

INTRODUCTION

This research project was designed to explore the use of ultra-high resolution thermal infrared imagery as a tool for improving hydrogeologic analysis and to suggest groundwater resource monitoring and management strategies for the State of Wisconsin. The premise of the work is that the thermal signature of groundwater is relatively constant year round, but differs from the stream temperature which varies on diel and annual cycles. As a result of the temperature contrast between surface water and groundwater, ultra-high resolution imagery of temperature (centimeter to decimeter scale) has the potential to be used to map groundwater discharge to streams and at seepage faces (external boundaries of the saturated zone).

Thermal remote sensing has been used to help understand stream temperature dynamics, calibrate and validate stream temperature models, map physical habitat variables, direct future monitoring efforts and monitor the success and/or failures of ecological restoration projects (Faux et al. 2001, Loheide and Gorelick 2006, Shuman and Ambrose 2003). Most thermal infrared studies involve the collection of thermal data in addition to visible color imagery or video to assist with geo-referencing and provide a visual overview of a study area. The most common airborne platforms for thermal infrared studies are fixed-wing aircraft and helicopters (Kay et al. 2001, Loheide and Gorelick 2006, Love et al. 2005, Sams III and Veloski 2003, Torgerson et al. 2001). Errors can be caused by variations in flight speed, sensor orientation to the ground, flight altitude and resolution of thermal imagery for airborne collection platforms. A prohibitive factor for both fixed-wing aircraft and helicopter data collection is cost; which ranges from $150/hour to $900/hour. The use of unmanned aerial vehicles (UAVs) with a payload capable of carrying imaging sensors has the potential to reduce the costs associated with data collection while simultaneously improving the quality and spatial resolution of the imagery collected.

The overarching objective of the project was the development of a cost-effective, transferrable methodology for the mapping of springs and groundwater discharge to streams. This work was targeted to fulfill a priority set forth by the Wisconsin Department of Natural Resources (DNR) in support of 2003 Wisconsin Act 310. Under Act 310, the DNR is required to review proposed wells that may impact a spring. A spring is defined as "an area of concentrated groundwater discharge occurring at the surface of the land that results in a flow of at least one cubic foot per second at least 80 percent of the time." Prior to this project, no simple or cost-effective methodology existed for conducting a reliable statewide spring inventory to locate potentially threatened springs using this definition.

The first component of the project involved differentiating between diffuse and focused groundwater discharge to streams through seepage faces, which are external boundaries of the saturated zone. Although only “concentrated groundwater discharge” to streams is protected by WI Act 310, both diffuse and focused groundwater discharge contribute to streamflow and both exert significant control on the ecology of aquatic systems. As a result, it is necessary to characterize both forms of groundwater discharge and their relative importance. To achieve this, ground-based thermal remote sensing was employed at a stream bank seepage face in order to demonstrate a new method to characterize the nature of groundwater flux. Prior to this work, no method existed to image groundwater processes along seepage faces. The purpose of this field study was to evaluate the use of ground-based, centimeter-scale thermal infrared imaging for characterizing groundwater flow at the stream bank.

The second component of this was a proof of concept intended to demonstrate that thermal remote sensing could be used for mapping stream temperature and identifying groundwater discharge to streams using airborne methods. This involved development of protocol for collecting and analyzing thermal imagery using both airplanes and UAVs. We compare the benefits and drawbacks of using thermal remote sensing from both an unmanned aerial vehicle (UAV) and small airplane for improved water management data acquisition in the State of Wisconsin

The third component is a case study that uses remotely sensed stream temperature data to quantify diffuse groundwater discharge to an ~11 km reach of the East Branch Pecatonica River (near Barneveld, Wisconsin). We show that this data can serve as the basis for quantifying the potential threat climate-warming may pose to cold-water fisheries in the region. The remotely-sensed thermal infrared imagery and in-situ temperature histories are used for validation of a numerical, spatially distributed stream temperature model. The model is then used to predict the streams thermal regime under future climatic conditions in order to determine its suitability for supporting brook trout and brown trout.

PROCEDURES AND METHODS

A) *Imaging diffuse and focused groundwater discharge at the seepage face with ground-based thermography*

Thermal imagery and digital photography were collected of the north and south sides of an incised drainage ditch in June 2008 and February 2009 A FLIR Systems (North Billerica, MA) A320 thermal infrared camera was used for data collection. The A320 measures surface temperature using a 320X240 focal plane array with a spectral range of 7.5 to 13 micrometers. A staph with 5 cm wooden dowel calibrations was used to measure distance in the thermal images. Three 8-inch diameter soil cores were extracted from the seepage face and analyzed in the lab for hydraulic conductivity using a falling-head permeameter; the three samples came from regions designated as high, moderate and low groundwater seepage intensity based on the thermal imagery. The elevation of the water table was continuously recorded using monitoring wells, equipped with pressure transducers, that were installed on both sides of the drainage ditch and were corrected with an on-site barometric logger. Air temperature and relative humidity were recorded continuously on-site using a HOBO ProV2 (Onset Computer Corp, MA) logger.

Twenty-four hours of thermal imagery was collected on July 3 and 4, 2008 of one location on the south side of the drainage ditch. Images of this region were recorded at a rate of 5/minute. Soil moisture along the seepage face (from the stream surface to the top of the stream bank) was measured using a theta probe (Delta T Devices, United Kingdom) at 5 cm increments immediately after the 24-hour data collection.

Thermal data correction accounted for emissivity, air temperature, relative humidity and the distance between the thermal infrared sensor and the seepage face. In this study, we assumed a uniform emissivity of 0.96 based on emissivity values of water (0.98-0.99), green vegetation (0.96-0.99), wet soil (0.95-0.98) and dry soil (0.92-0.94).

Data analysis included the creation of temperature profiles and estimation of the height of the water table above the stream. A program was developed to average the temperature in each row of each 320X240 thermal image and determine the vertical range of pixels that clearly were located within the saturated zone as well as a range clearly within the unsaturated zone based on thermal signature. Lines were fit to data from each zone to describe the temperature as a function of depth. The intersection of the two best-fit lines represents the transition between the saturated and unsaturated zones and is also taken as the position of the water table, because a soil characteristic curve adjacent to the channel indicates that the capillary fringe is small (<10cm). Height in centimeters was approximated using the wooden dowel scale bar present in each thermal image.

B) *Airborne mapping of springs and diffuse groundwater discharge: Development and comparison of single-engine airplane and UAV approaches*

A forward-looking infrared camera was mounted to a custom-made, unmanned aerial vehicle (UAV) to collected thermal remote sensing data. Data was transferred from the UAV platform to a laptop computer on the ground using a wireless Ethernet bridge. A small computer was attached to the UAV to store imagery and operate the camera. This computer was controlled by a ground-based laptop, using a remote desktop connection over the wireless Ethernet bridge. This allowed ground-to-plane focusing of the camera, but did not have sufficient bandwidth to continuously transfer images to the ground. Following each flight, data was transferred from the UAV computer to the laptop using a flash drive. FLIR Researcher (FLIR Systems, North Billerica, MA) software was used to collect and analyze the thermal data. We typically recorded imagery at 1 Hz, with corresponding visual photographs at the same interval.

A small digital camera was used to obtain visible photographs of the streams under study. SLR and digital photographs provide a point of reference for thermal images and are useful for geo-referencing because they provide a better understanding of surrounding features. For example, the visible images can help distinguish between water in the stream channel and the stream bank (which often have a similar temperature) in the corresponding FLIR image. Photos were downloaded and geo-referenced using GPS waypoint data collected with a Garmin Etrex Vista GPS unit. The GPS unit was mounted to the UAV in order to obtain continuous location data for ortho-rectification of FLIR and visible images.

The use of UAVs in the US requires permission from the Federal Aviation Administration (FAA) when small, unmanned aircraft are used for research purposes while flights of equivalent aircraft for recreational purposes are not subject to the same regulation process. UAV flights for commercial purposes have currently not been approved in the US, but public universities and government agencies are allowed to designate UAVs as 'public aircraft,' through the FAA Certificate of Authorization (COA) process, which allows UAVs to be used for research and monitoring, in projects such as this one. The FAA process requires permitting including determination of airworthiness, landowner permissions, safety and hazard protocol development and approval from the Federal Communications Commission for use of radio controls. During this project, we obtained a COA allowing us to conduct UAV flight operations at the East Branch Pecatonica River near Barneveld, WI and Allen Creek near Ft. Atkinson, WI.

In addition to UAV flights, thermal remote sensing data was collected using aircraft owned by the WI Department of Administration and flown by pilots from the WI Department of Natural Resources. These flights were conducted using either a single-engine Cessna with a belly hole installed for the specific purpose of collecting aerial imagery or using a twin-engine Skymaster with a cargo hold capable of housing cameras that can be controlled from the aircraft cabin. Flight altitude was approximately 500 ft. Because of limited maneuverability and inability to track sinuous streams at low altitude, repeat flights were conducted to obtain complete coverage. In-stream measurements of the time rate of change in stream temperature were used to adjust remotely sensed stream temperature estimates from the time an individual image was collected to nominal time, midway through a flights data collection period.

Assessment of the accuracy of the methods required ground truthing of remotely sensed stream temperature with insitu measurements. Ground truthing included the installation of 11 HOBO Prov2 in-stream temperature data loggers at the East Branch Pecatonica and 4 at Allen Creek (Onset Computer Corp, MA). The HOBOS were used to construct in-stream temperature histories, verify FLIR thermography data and aid in the temporal validation of the stream temperature model. The Prov2 loggers have twelve-bit resolution with an accuracy rating of +/- 0.2ºC over a wide range of temperatures.

C) *Case Study: Stream temperature, groundwater discharge, and the future of effects of climate change on coldwater fisheries in the Driftless area of WI.*

On July 24, 2008, thermal imagery was collected over an 11km reach of the upper East Branch Pecatonica from a single-engine airplane using a FLIR A320 (North Billerica, MA) thermal infrared camera. Flights occurred at four times throughout the day. Temperature profiles were created by sampling rectangular regions of interest consisting of 8-25 pixels at twenty identical locations for each of the four flight times.

Ground-truth data were used to assess the accuracy of remote sensing-based estimates of stream temperature and for validation of the stream temperature model, included three in-stream temperature data loggers (HOBO Water Temp Pro v2, Onset Computer Corporation). Duplicate stream flow measurements were taken at each of the three ground truth locations using an acoustic Doppler velocimeter (Son Tek). Weather data, including air temperature, solar radiation, humidity and wind speed, were recorded using a HOBO weather station.

Stream temperature was modeled using Heat Source V.8.0.4, distributed by the Oregon Department of Environmental Quality (ODEQ) (http://www.deq.state.or.us/wq/TMDLs/tools.htm), following the methods outlined by Boyd and Kasper (2003). Heat Source is a finite difference code that solves the one-dimensional, transient, advection-dispersion equation and accounts for heat exchange associated with the process of stream bed conduction, air convection, solar loading, evaporation/condensation, and groundwater inflow. The model's user interface is Microsoft Excel; however, computations run externally using Python 2.5.

The East Branch Pecatonica is located in the Driftless Area of Wisconsin, a region well known for its trout streams which may be threaten by future climate warming. The stream temperature model was used to simulated the future thermal regime of the stream considering future scenarios in which air and groundwater temperature increase by 1, 3 and 5°C and streamflow increases or decreases by thirty percent. The resulting thermal regime was compared to the thermal niche of brook trout and brown trout determined by Wehrly et al. (2007), to determine the future thermal suitability of the streams for these cold-water species. The work demonstrates the utility of spatially extensive thermographic profiles, derived from thermal imaging, for stream temperature model validation. Additionally, it highlights the importance of groundwater discharge on stream temperature dynamics with implications for fisheries management under future climatic conditions.

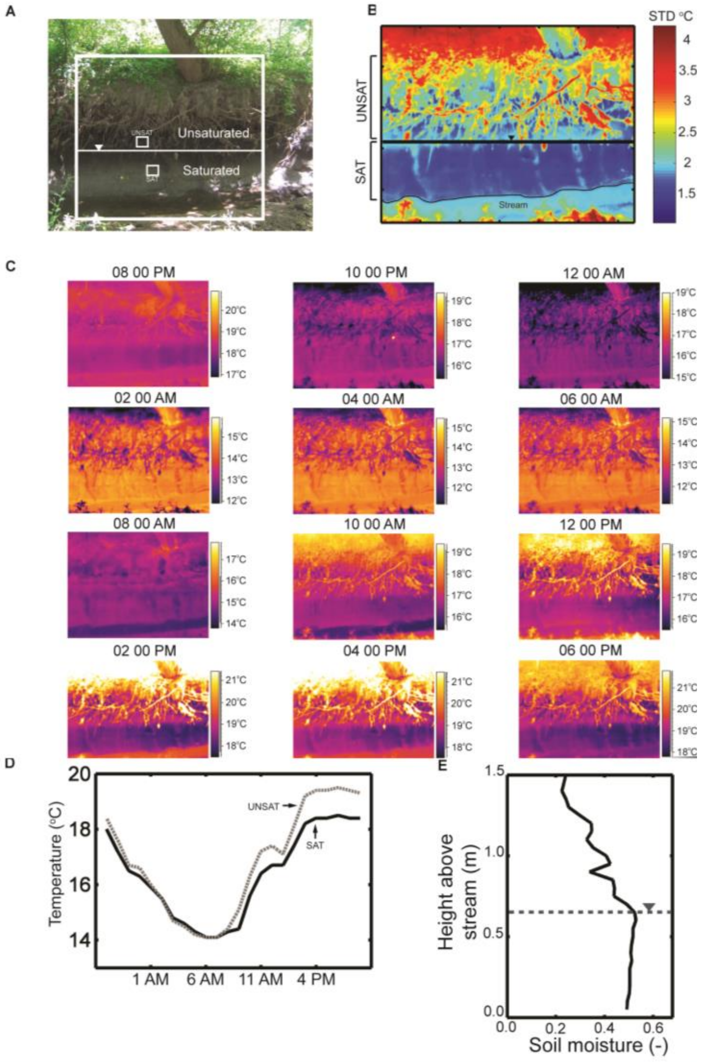
RESULTS AND DISCUSSION

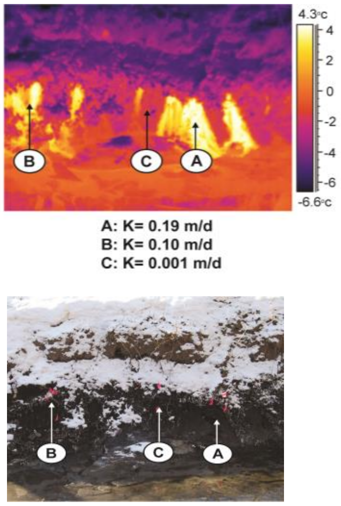
A) Imaging diffuse and focused groundwater discharge at the seepage face with ground-based thermography

Time-lapse thermal imagery, collected over a 24-hour period of a stream bank (Fig 1A) clearly indicates dissimilar unsaturated zone and saturated zone thermal inertia. Recorded temperatures in two regions of interest (UNSAT and SAT), selected in areas free of stream bank vegetation, highlight the contrast between saturated and unsaturated zone diurnal temperature variability of the stream bank (Fig 1D). Saturated zone and unsaturated zone temperatures follow the same trend as atmospheric temperature; however, the saturated zone temperature maximum, and to a lesser extent minimum, are muted relative to the unsaturated zone temperature. The buffered thermal variation in the saturated zone can be seen as a reduced standard deviation of temperature imaged over the daily cycle in Fig 1B.

Diurnal temperature changes confirm that peak atmospheric temperature is the optimal time to collect thermal imagery of groundwater. The time-lapse thermal imagery, demonstrates that from 3:30 – 5:00 PM, the unsaturated zone – saturated zone temperature difference is greatest. In the 2:00 PM and 4:00 PM snapshots in Fig 1C, the saturated zone appears as the cooler zone (<18.5ºC), which is separated from the warmer unsaturated zone above by the water table and the warmer stream below by the stream surface. The saturated zone appears as a slightly warmer band relative to the overlying unsaturated zone and underlying stream in the 4:00 AM and 6:00 AM snapshots. It is recommended that thermal imaging of groundwater be performed at seasonal atmospheric temperature highs or lows and maximum or minimum daily temperatures, respectively. At that time, the air-saturated zone temperature difference is greatest and the resulting thermal signature of groundwater will be most clearly evident. As a result, it is possible to image the transition between the saturated and unsaturated zone at the seepage face during those times. As confirmed by soil moisture measurements (Fig 1E) and water table depth measurements (not shown), ground-based thermal imagery allows for identification of the water table position at the seepage face scale and this method can be used to obtain spatially extensive water table elevation data.

Hydraulic conductivity (K) measurements of three soil cores collected in February 2009 in one thermal image frame (Figure 2) indicate that areas of high groundwater seepage correlate with high K soils whereas areas of lower groundwater seepage intensity correlate with lower K values. During collection of winter thermal imagery, regions of high groundwater discharge are warmer than regions with lower groundwater discharge since the latter are more strongly affected by cold air temperatures and the former are buffered by groundwater. Figure 2 clearly shows distinct regions of focused groundwater discharge (labeled A, B, and C) whereas fig 1 captured a more uniform region of diffuse groundwater discharge. It is important to note that these portions of the streambank dominated by diffuse and focused groundwater discharge showed the same spatial pattern in both summer and winter with inverted temperature trends, and the difference in the nature of discharge between Fig 1 & 2 is a result of spatial, not temporal, differences. In Figure 2, the high intensity, warm seepage region (A) has a hydraulic conductivity nearly 200 times greater than the hydraulic conductivity of the low intensity seepage region (C). This indicates that the thermal heterogeneity of the seepage face is a result of variability in hydraulic conductivity.





A: K= 0.19 m/d
B: K= 0.10 m/d
C: K= 0.001 m/d

Figure 1: (left) – Time-lapse thermal data collected at one stream bank: *A)* Thermal image showing two regions of interest (SAT – saturated zone, UNSAT – unsaturated zone). *B)* Standard deviation of the 24 hour time lapse data, which exhibits the lower thermal inertia of the unsaturated zone. *C)* Thermal images at two-hour intervals *D)* 24 hour average temperature history of two regions of interest (SAT and UNSAT) *E)* Vertical soil moisture profile (5 cm increments) from the stream to the top of the stream bank.

Figure 2: (above) – Winter thermal imagery showing correlation between hydraulic conductivity and imaged seepage intensity

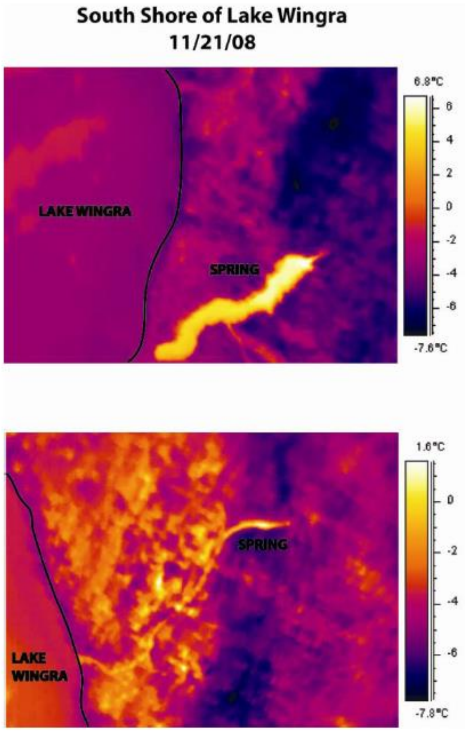


Figure 3: Thermal imagery of spring flow into Lake Wingra, Madison, Wisconsin collected from a fixed-wing aircraft. The imagery was collected in November 2008, when the groundwater temperature is warmer than the surface

B) Airborne mapping of stream temperature, springs and diffuse groundwater discharge: Development and comparison of single-engine airplane and UAV approaches

Stream temperature was successfully mapped using airborne remote sensing from both small airplane and UAV platforms. UAV data collection occurred on multiple flight dates at the East Branch Pecatonica and at Allen Creek. Due to FAA restrictions, flights were limited to short stream reaches at two sites. Airplane based thermal remote-sensing were conducted several times during both summer and winter at sites including Allen Creek, the East Branch Pecatonica River, Lake Wingra, and Blue Mounds Creek.

Springs were easily observed from thermal remote sensing. Fig 3 shows a large and relatively smaller spring on the shore of Lake Wingra in December of 2008 imaged from a small airplane. During the collection period, the land surface is cold and the relatively warmer groundwater discharge from springs is clearly evident. During the summer, springs appear cool relative to the surroundings and the temperature contrast is greater, but smaller springs in forested regions are obscured by vegetation and difficult to locate.

Figure 4 shows thermal imagery at the East Branch Pecatonica River collected from the UAV platform. In Fig 4A, the remote sensing-derived stream temperature of 18.2°C is within 0.4°C of the temperature recorded by an in-stream data logger (approximately 20 meters downstream) at the time of flight, and in Fig 4D, stream temperature measured from remote sensing is within 0.2°C of the in-stream temperature. The methodology produces ultra-high resolution stream temperature images within the threshold of 0.5°C accuracy that has been reported by Torgerson et al. (2001). Furthermore, images in Figure 4 show little to no variability in stream temperature within a single image, indicating no locations of focused groundwater discharge that are volumetrically significant when compared to the stream discharge. As will be discussed in the next section, the stream reach shows gradual variation in stream temperature resulting from spatially variable diffuse groundwater discharge to the stream. The variability in land surface temperature is the result of differences in transpiration rates of the vegetation at the site, which has recently been the focus of restoration efforts.

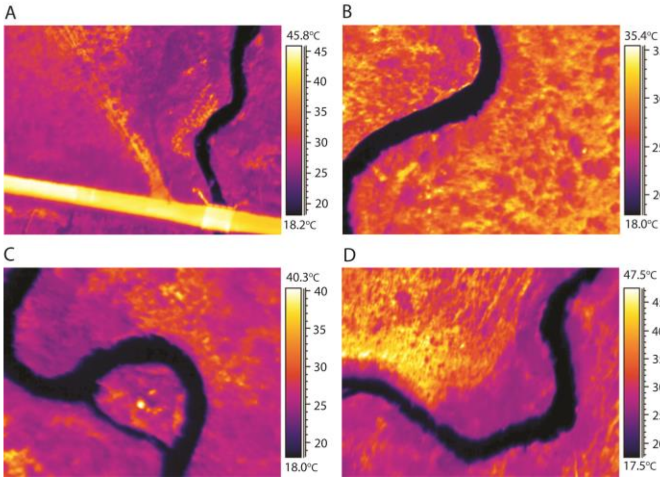


Figure 4: Thermal imagery collected from the UAV at the East Branch Pecatonica 2006 restoration site in July 2008. The straight, left-right trending feature in panel A is a road, which appears warm relative to its surroundings in the thermal image. The imagery was collected in the afternoon on a warm summer day.

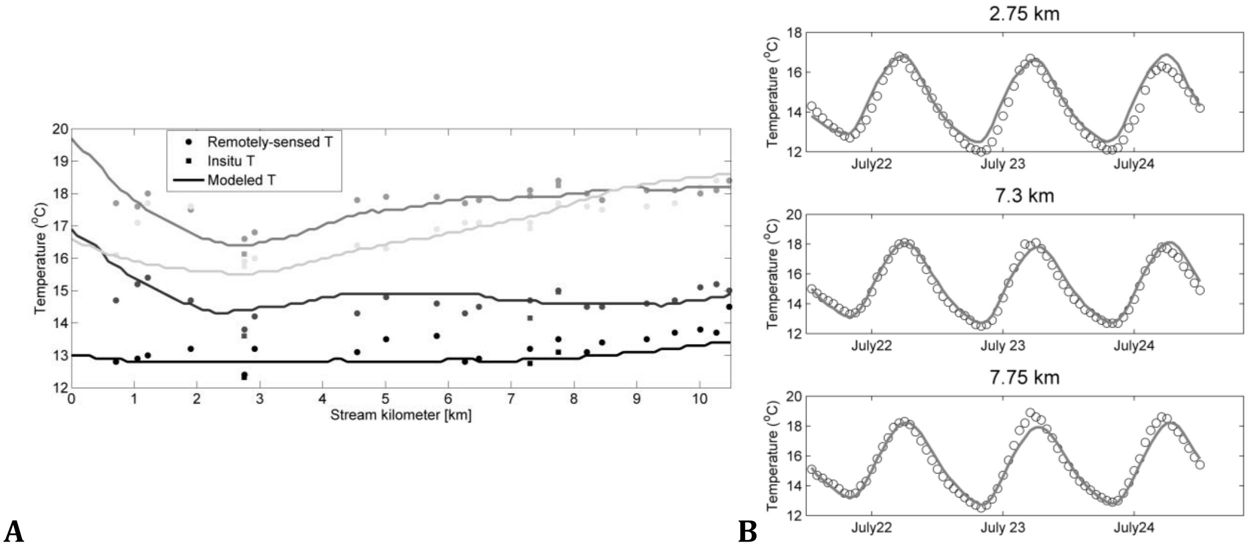


Figure 5: A) Comparison of remotely sensed, in-stream, and simulated temperature on July 24, 2008 for the East Branch Pecatonica River. The profile moves downstream left to right (0 km is upstream, 10.47 km is downstream). B) Comparison of simulated (line) and measured (circles) stream temperature at the locations of the three in-stream data loggers.

C) *Case Study: Stream temperature, groundwater discharge, and future effects of climate change on coldwater fisheries in the Driftless area of WI.*

Remotely-sensed thermographic profiles collected from a single-engine airplane and in-stream temperature histories were used in validating a one-dimensional stream temperature model to assess the threat of global climate change to ecologically and economically valuable trout fisheries in southwest Wisconsin. Figure 5A shows longitudinally sampled FLIR-based estimates of stream temperature, in-situ stream temperature measurements at 2.75 km, 7.3 km and 7.75 km and simulated temperatures throughout the reach. The mean absolute difference between remotely sensed estimates of stream temperature and in-situ measurements at the three continuous nodes is 0.25°C, which is consistent with previous studies that report accuracy of FLIR-based estimates of stream temperature of +/- 0.5°C (Loheide and Gorelick 2006, Torgerson et al. 1999). Simulated and observed records of stream temperature (Figure 5B) at the three continuous observation stations have root mean squared error (RMSE) values of 0.4°C at 2.75 km, 0.35°C at 7.3 km and 0.39°C at 7.75 km. This best fit was obtained by varying groundwater inflow across the reach; final modeled input of groundwater inflow at 5-meter increments varies spatially between 0.0005 and 0.0035 m3/s (Figure 6). Simulated and observed stream flows at the three observation stations have a mean absolute difference of 0.013 m^3/s.

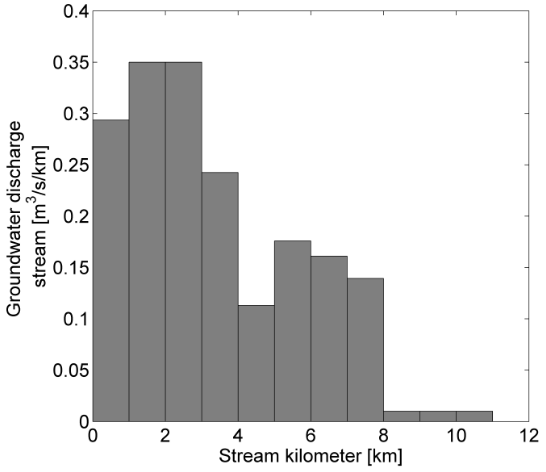


Figure 6: Longitudinal profile of groundwater discharge to the East Branch Pecatonica River determined using stream temperature modeling to match remotely-sensed stream temperature profiles

The best-fit model was achieved with groundwater inflow nearly three times greater between 1.75 and 3 km than at adjacent stretches. This corresponds with a depression in stream temperature, shown in Figure 5 and is comparable to the variability in baseflow observed by Loheide and Gorelick (2006) using thermal remote sensing methods in California. Without the high spatial resolution of thermal infrared data, the significant depression in stream temperature from ~1.5 – 3 km would not be easily identified. In the summer, baseflow reduces the maximum daily temperature due to the discharge of cool groundwater. At 07:00 AM (the earliest flight), there is no depression in stream temperature from 1.5-3 km because the stream temperature is roughly equal to the groundwater temperature (~12.9°C) throughout the stream length. At 03:00 PM, the flight closest to the peak daily air temperature, the influence of groundwater is most pronounced because the difference between groundwater and stream temperature is greatest. At 03:00 PM, stream temperature varies by up to 3°C from 0 km to 10.47 km. Further downstream, the marginal thermal (cooling) effect of equal baseflow is less than upstream because stream flow is greater. As a result, variations in baseflow are not as evident downstream in the simulated and observed temperature histories.

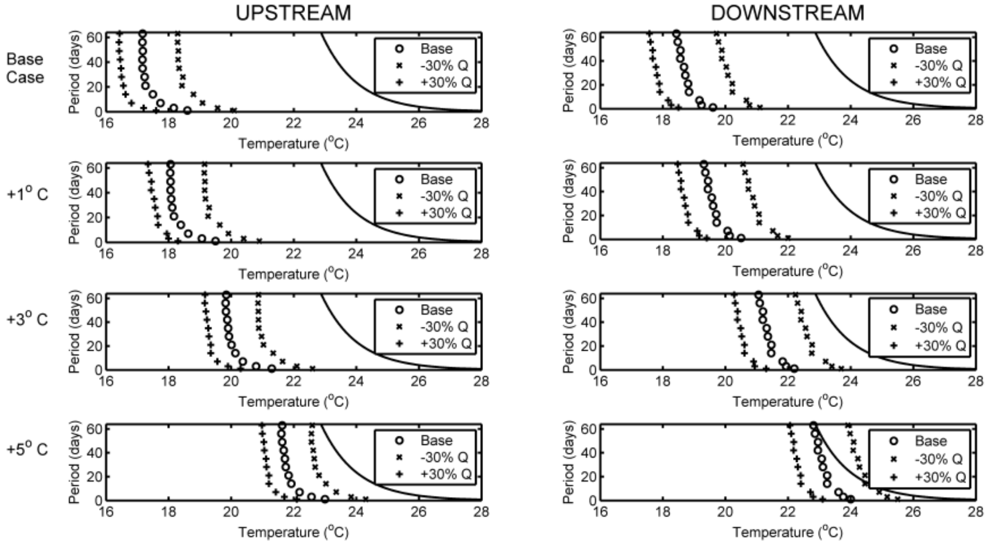


Figure 7: Comparison of simulated cases at an upstream (2.75 km) and downstream (7.75 km) location to the maximum daily maximum curve (solid line) developed by Wehrly et al. (2007). The absolute difference between the base case and the change in stream flow cases is greater at the downstream location for all simulations. Only the +5°C, -30% stream flow case crosses the empirical threshold developed by Wehrly et al. (2007).

Twelve stream temperature model simulations were used to estimate the potential threat from elevated stream temperature to brook and brown trout at the upper East Branch Pecatonica River. Both increases in air and groundwater temperature and decreases in stream flow drive daily maximum stream temperature higher and in combination threaten the fishery of the small stream studied here. In the most extreme scenario, stream temperature crosses thermal tolerance thresholds (Fig 7) developed for similar, low-order, high groundwater discharge, fisheries in Wisconsin and Michigan (Wehrly et al. 2007). This study demonstrates that while climate warming poses a risk to trout fisheries in southwest Wisconsin, the magnitude of these effects cannot be predicted without good estimates of groundwater discharge, it's spatial variability, and it's expected future trend. Site-specific conditions, such as stream flow and stream width-to-depth ratios, are critical controls on stream temperature, and therefore the magnitude of the effects of climate warming. Thermal infrared and in-stream data may be used in combination to validate a freely available one-dimensional stream temperature model to predict the impacts of climate change on stream temperature. Thermal tolerance thresholds, such as the maximum daily maximum stream temperature developed by Wehrly et al. (2007), may be used to assess species' risk.

CONCLUSIONS AND RECOMMENDATIONS

Airborne and ground-based thermal remote sensing data collection can be used to improve Wisconsin's water management program, supplement hydrologic data sets and improve conceptual and quantitative models of groundwater flow. Thermal remote sensing is an easily transferrable method that uses heat as a natural tracer of groundwater discharge. It can image groundwater flow at decimeter to centimeter resolution. This research project demonstrates that thermal remote sensing: (1) provides a method to observe the water table and groundwater discharge processes at the seepage face, (2) provides ultra-high resolution imagery of stream temperature, (3) can be used to map springs and quantify diffuse groundwater discharge to streams (4) provides strong validation data for stream temperature modeling, and (4) may assist the State of Wisconsin in promoting sustainable use of groundwater and protecting spring resources. This research involved data collection at three different sites in Wisconsin: (a) the East Branch Pecatonica River, (b) Allen Creek and (c) The University of Wisconsin-Madison Arboretum.

Ground-based thermal imaging of groundwater in the University of Wisconsin Arboretum provides a method to (1) observe the water table using thermal imagery, (2) enhance conceptual models of geologic heterogeneity and (3) distinguish between focused and diffuse groundwater discharge to the surface. Thermal imagery collected on both sides of a stream bank seepage face showed groundwater flow as both a locally discrete and locally diffuse process. Additionally, twenty four hours of time-lapse thermal imagery demonstrated that peak air temperature, when the gradient between air and groundwater temperature is greatest, is the ideal time window to collect thermal imagery of groundwater. Hydraulic conductivity measurements, measured using a falling-head permeameter, validated the data interpretation by revealing a correlation between remotely-sensed seepage intensity and hydraulic conductivity; higher hydraulic conductivity is correlated with higher intensity seepage. Imaging of groundwater flux variability has significant implications for hydrogeologic understanding of heterogeneity and has applications to research on the scale dependencies of hydraulic conductivity, contaminant transport, groundwater flow modeling and ecohydrology. New thermal imaging methods employed in this study provide a technique to display heterogeneity at the centimeter to seepage face scale. Although the method is limited to outcrops and seepage faces, the resulting insight on system heterogeneity has applicability for hydrogeologic setting.

Both small airplanes and UAVs were determined to be viable platforms for collecting thermal imagery of streams in Wisconsin. Both methods resulted in remotely sensed temperature measurements that were in good agreement (within 0.5°C) of insitu measurements. In both cases, springs could readily be identified from the imagery. UAV flights indicated that the thermal resolution of stream temperature maps can be up to three times greater than the resolution of imagery collected from small airplanes at greater flight altitudes. However, our UAV flights were limited to the line of sight of the operator and therefore UAV based stream temperature surveys where much more spatially limited than when manned-airplanes were used, which enabled catchment-scale surveys to be conducted. The data showed that UAVs are a viable alternative to small airplanes and may be employed to study finer scale processes (e.g. smaller springs). The key implication of this work is that thermal remote sensing may be used as a reconnaissance tool for locating springs and may aid the State of Wisconsin in administration of Act 310.

Thermal imagery collected at the East Branch Pecatonica River, was used to validate a stream temperature model forecasting potential changes in stream temperature as a consequence of climate change. By matching the simulated stream temperature with the observed stream temperature, we were able to quantify the spatial distribution of diffuse groundwater discharge to the stream. We then used the model to simulate future stream temperature regimes that would result from climate change scenarios that included combinations of an air temperature/groundwater temperature increase of 1, 3 and 5°C and changes in stream flow of -30% baseflow and +30% baseflow. The data reveal that in the more extreme climate change scenarios (e.g. increase in air and groundwater temperature of 5°C and thirty percent less baseflow), native brook trout and non-native brown trout populations may be thermally stressed. Without the remotely-sensed thermal data, a sub-reach with higher groundwater discharge that serves as a thermal refuge even in climate change scenarios would not have been located. This finding is particularly important in the Driftless Area because the region benefits with greater than $1 billion in annual expenditures on recreational trout angling (Trout Unlimited, 2008) and suggests a means by which fishery conservation efforts may be prioritized within a watershed.

REFERENCES

Boyd, M. and B. Kasper. 2003. Analytical methods for dynamic open channel heat and mass transfer. Methodology for the Heat Source model version 7.0. http://www.deq.state.or.us/wq/TMDLs/docs/tools/heatsourcemanual.pdf.

Faux, R.N., Lachowski, H., Maus, P., Torgerson, C.E., Boyd, M.S. 2001. New approaches for monitoring stream temperature: airborne thermal remote sensing. US Department of Agriculture Forest Service Engineering Remote Sensing Applications Center. 29 p.

Kay, J., Handcock, R.N., Gillespie, A., Konrad, C., Burges, S., Naveh, N., Booth, D. 2001. Stream temperature estimation from thermal infrared images. International Geosciences and Remote Sensing Symposium. 3 p.

Loheide, S.P. II, Gorelick, S.M. 2006. Quantifying stream-aquifer interactions through the analysis of remotely sensed thermographic profiles and in situ temperature histories. *Environmental Science and Technology* 40, no. 10. 3336-3341.

Love, E., Hammack, R., Harbert, W., Sams, J., Veloski, G., Ackman, T. 2005. Using airborne thermal infrared imagery and helicopter EM conductivity to locate mine pools and discharges in the Kettle Creek watershed, north-central Pennsylvania. *Geophysics* 70, no. 6. B73-B81.

Sams III, J.I., Veloski, G.A. 2003. Evaluation of airborne thermal infrared imagery for locating mine drainage sites in the Lower Kettle Creek and Cooks Run Basins, Pennsylvania, USA. *Mine Water and the Environment* 22, no. 2. 85-93.

Shuman, C.S., Ambrose, R.F. 2003. A comparison of remote sensing and ground-based methods for monitoring wetland restoration success. *Restoration Ecology* 11. 325-333.

Torgerson, C.E., Faux, R.N., McIntosh, B.A., Poage, N.J., Norton, D.J. 2001. Airborne thermal remote sensing for water temperature assessment in rivers and streams. *Remote Sensing of the Environment* 76, no. 3. 386-398.

Trout Unlimited/North Star Economics, Inc. The economic impact of recreational trout angling in the Driftless Area. April 2008.

Wehrly, K.E., L. Wang, and M. Mitro. 2007. Field-based estimates of thermal tolerance limits for trout: incorporating exposure time and temperature fluctuation. Transactions of the American Fisheries Society 136: 365-374.

APPENDIX A: Awards, Publications, Reports, Patents and Presentations

1) Deitchman, R.S., and S.P. Loheide II (2009), Characterization of groundwater flux using ground-based thermal remote sensing at the seepage face, American Water Resources Association – WI Section 2009 Annual Meeting, Stevens Point, WI. “Best Student Platform” award winner.
2) Deitchman, R.S, (2009), Thermal remote sensing of stream temperature and groundwater discharge: Applications to hydrogeology and water resources policy in the state of Wisconsin, M.S. Thesis, UW-Madison.
3) Deitchman, R. S., and S. P. Loheide II (2009), Ground-based thermal imaging of groundwater flow processes at the seepage face, Geophys. Res. Lett., 36, L14401, doi:10.1029/2009GL038103.
4) Deitchman, R.S. and S.P. Loheide II (In review), Impacts of climate change on stream temperature and fish habitat of a Driftless Area trout stream.
5) Loheide, II, S.P. (2009), Characterization of groundwater processes in riparian areas using thermal remote sensing, NovCare 2009, Leipzig Germany
6) Loheide, II, S.P., (2007), Thermal remote sensing detection of groundwater discharge to streams, Invited Presentation, Geological Society of America Annual Meeting, Denver