Report as of FY2008 for 2008WI192B: "A Thermal Remote Sensing Tool for Mapping Spring and Diffuse Groundwater Discharge to Streams"

Publications

- Articles in Refereed Scientific Journals:
  - Deitchman, R and S. Loheide. 2009. Ground-based thermal imaging of groundwater flow process at the seepage face. Accepted for publication, Geophysical Research Letters.

Report Follows

Annual Progress Report

Selected Reporting Period: 7/1/2007 - 6/30/2008

Submitted By: Richard Deitchman
Submitted: 5/27/2009

Project Title

WR07R005: A Thermal Remote Sensing Tool for Mapping Spring and Diffuse Groundwater Discharge to Streams

Project Investigators

Steven Loheide, University of Wisconsin-Madison

Progress Statement

The first research objective of this project is the use of thermal remote sensing data, collected from both a single-engine airplane and an unmanned aerial vehicle (UAV), for mapping of spring and diffuse groundwater discharge to streams in Wisconsin. The temperature of groundwater is relatively constant, whereas surface water temperature varies on seasonal and diurnal cycles. As a result of this thermal signature, it is possible to locate groundwater discharge using thermal imaging. Progress towards this research objective during the reporting period (3/1/2008-2/29/2009) includes:
• Completion of four separate thermal imaging flights over the East Branch Pecatonica River field site (7 AM, 11 AM, 3 PM and 7 15 PM) to assess large-scale stream temperature dynamics. [7/2008]
• Field data collection, including in-stream data logger installation and stream gaging, for comparison to remotely-sensed data and for stream temperature modeling [3/2008-2/2009]
• Processing of thermal infrared data to develop longitudinal profiles of stream temperature [7/2008-12/2008]
• Development and completion of a one-dimensional stream temperature model using data from the July 2008 thermal imaging flights and from in-stream data loggers as validation. We used Heat Source, distributed by the Oregon Department of Environmental Quality, for our simulations. [3/1/2008 - 2/29/2009]
• Field testing of the UAV system at the East Branch Pecatonica River (near Barneveld, WI) and Allen Creek (near Ft. Atkinson, WI) [3/2008-2/2009]
• Assessment of the policy and legal implications of thermal remote sensing from both a single-engine airplane and UAV for the State of Wisconsin [8/2008-2/2009]
• Preparation of manuscript titled, " Simulating the impacts of climate change on the temperature of a Driftless Area trout stream using remotely sensed thermographic profiles and in-stream temperature histories" [3/2008 - current]

A second research objective of this work is to use thermal remote sensing to distinguish between focused and diffuse groundwater discharge. In 3/2008, thermal imagery revealed fine-scale (centimeter) variability in groundwater discharge through seepage faces that could best be investigated using ground-based thermography. In conjunction with an ongoing study on the effects of current and future stormwater management practices on the hydroecology of West Wingra Marsh in the University of Wisconsin Arboretum, ground-based thermal remote sensing was employed at a stream bank seepage face in order to characterize the nature of groundwater flux. No method exists to image groundwater processes along seepage faces, which are external boundaries of the saturated zone. 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. Seepage faces are often poorly understood, although they may exert a significant influence on the eco-hydrology of riparian areas. The imagery provides a method to visualize point and diffuse discharge at the centimeter scale and characterize the degree of heterogeneity of the

hydraulic properties of the sediment. Progress towards this research objective during the reporting period (3/1/2008-2/29/2009) includes:

• Reconnaissance collection of thermal imagery of seepage faces at a drainage ditch in West Wingra Marsh to compare longitudinal variation in the height of the groundwater seepage face, seepage face intensity and the nature of groundwater flow (focused vs. diffuse discharge). [3/2008-6/2008]

• Collection of imagery on both sides of the seepage face to characterize processes at the stream reach scale [6/2008]

• Collection of 24 hours of continuous thermal imagery at one location along the Wingra Marsh drainage ditch to assess diurnal variation in seepage face temperature. Observed differences in thermal inertia allow detection of water table position, regimes of higher groundwater flux, and variation in soil moisture in the vadose zone [7/2008]

• Collection of winter thermal imagery for comparison to the summer data set [2/2009]

• Collection of three, 8" diameter soil cores and permeameter testing to assess hydraulic conductivity of the stream bank sediments [2/2009]

• Statistical analysis and image processing of seepage face data [3/2008-2/2009]

• Presentation by Deitchman at American Water Resources Association - Wisconsin Section 2009 Annual Meeting [3/5/2009 - won "Best Student Platform" presentation award]

• Preparation of manuscript for Geophysical Research Letters, titled "Ground-based thermal imaging of groundwater flow processes at the seepage face" [submitted 3/2009, accepted pending minor revisions on 5/11/2009]

Principal Findings and Significance

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Description

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) provides strong validation data for stream temperature modeling, (4) can be used in conjunction with stream temperature modeling to quantify groundwater discharge to stream and (5) 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: (1) East Branch Pecatonica River, (2) Allen Creek and (3) The University of Wisconsin-Madison Arboretum. Thermal imagery collected from both an unmanned aerial vehicle (UAV) and from a small-airplane at the East Branch Pecatonica River, was used to validate a stream temperature model which was used for forecasting potential changes in stream temperature as a consequence of climate change (Figure 1). The model simulates stream temperature change with three air temperature/groundwater temperature increase scenarios (1, 3 and 5°C) and changes in stream flow (-30% baseflow and +30% baseflow) (Figure 2). 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 experience mortality due to exceedance of acceptable thermal regimes. 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).

In addition to small airplane work at the East Branch Pecatonica River, UAV flights at the site indicated that 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 (Figure 3). The data showed that UAVs are a valuable alternative to small airplanes and may be employed to study finer scale processes (e.g. smaller springs). However, regulations by the Federal Aviation Administration (FAA) limit UAV operation to pre-approved sites, with flight range restricted to the operators line of sight. Figure 4 shows thermal imagery collected from a single-engine airplane and highlights the use of thermal imaging for spring identification.

Ground-based thermal imaging of groundwater in the University of Wisconsin Arboretum provides a method to (1) identify water table position 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 a both locally discrete and locally diffuse process. Additionally, twenty four hours of time-lapse thermal imagery demonstrated that during the summer months, peak air temperature, when the difference between air and groundwater temperature is greatest, is the ideal time window to collect thermal imagery of groundwater (Figure 5). Hydraulic conductivity measurements, obtained with a falling-head permeameter, validated the data interpretation by revealing a positive correlation between remotely-sensed seepage intensity and hydraulic conductivity seeps (Figure 6).
Wisconsin water managers and policy makers would benefit from the use of thermal remote sensing. However, there are numerous regulatory hurdles, including Federal Aviation Administration regulations and technical deficiencies, that will limit the implementation of unmanned aerial vehicle thermal remote sensing for spring management in the state. Overcoming or complying with these requirements, thermal remote sensing from small airplanes and ground-based efforts will assist in groundwater supply management efforts and help protect valuable spring resources and ecosystems.

Description

Figure Captions:

Figure 1a:
Comparison of remotely-sensed (RS), in-stream (In) and simulated (Sim) temperatures 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). Remotely-sensed temperatures were sampled using a thermal infrared camera. In-stream records at 2.75 km, 7.3 km and 7.75 km were recorded using HOBO loggers. Simulated temperatures were modeled using Heat Source V.8.0.4 software.

Fig 1b:
Longitudinal profile of groundwater discharge to the stream estimated through stream temperature modeling.

Figure 2:
Maximum daily temperature for model simulations of the base case (no change in air/groundwater temperature or recharge), the base case plus 1°C, the base case plus 3°C and the base case plus 5°C at 7.75 km [top]. Maximum daily temperature for model simulations of the base case (no change in air/groundwater temperature or recharge), the base case -30% recharge and the base case +30% recharge at 7.75 km [bottom]. A decrease in recharge decreases the volume of stream flow allowing the stream to warm more readily.

Figure 3:
Thermal imagery collected from the unmanned aerial vehicle 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, and the stream is very cool relative to the land surface.

Figure 4:
Thermal imagery of spring flow into Lake Wingra (south shore), Madison, Wisconsin collected from a fixed-wing aircraft. The imagery was collected in November 2008. The groundwater temperature is warmer than the surface in winter (November in Wisconsin) consequently the springs appear as the warm locations in the thermal imagery (approximately 2-6ºC). The top frame displays a large spring whereas the bottom frame is a much smaller spring.

Figure 5:
Twenty-four hours of continuous 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 twenty-four hour time lapse data, which exhibits the lower thermal inertia of the

unsaturated zone. C) Twelve thermal images at two-hour intervals D) Twenty-four 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 6:
Winter thermal imagery and location of soil cores with hydraulic conductivity measurements: A)Winter visible image of seepage face with soil core locations annotated. B) Winter thermal imagery of seepage face with soil core locations and hydraulic conductivity values (K) [A= high intensity seepage, B= moderate intensity seepage, C= low intensity seepage]. Note: snow cover prevents interpretation of the thermal image above the seepage zone.

*note - figures are provided on iPro (My Activities Files --> Supporting Figures) and are labeled Figure 1-6

Interactions

Description

Organization/Agency: The Nature Conservancy
Category: Non-governmental organizations
Contact Name: Steve Richter
Contact Email: srichter@tnc.org
Description: Landowners of East Branch Pecatonica field site; provide site support and permissions; conduct quarterly science meetings to discuss research findings and implications for ongoing restoration activities at the site.

Event Date

Description

Organization/Agency: Wisconsin Department of Natural Resources
Category: Local and State
Contact Name: Bob Hansis
Contact Email: Robert.Hansis@Wisconsin.gov
Description: Advice for field activities near East Branch Pecatonica field site, assistance with single-engine airplane flights through the use of DNR pilots and state of Wisconsin aircraft, conduct quarterly science meetings to discuss research findings and implications for ongoing restoration activities at the site.

Event Date

Description

Organization/Agency: Friends of Allen Creek Watershed (FACW)
Category: Local
Contact Name: Andy Selle
Contact Email: aselle@interfluve.com
Description: Coordination of addition of Allen Creek to project study sites and assistance with completion of FAA permitting. FACW will use the spring inventory we develop for the watershed to plan restoration and conservation efforts. We plan to conduct field work in late summer 2008 and winter 2008.

Event Date

Description

Organization/Agency: Friends of Cherokee Marsh (FOCM)
Category: Local
Contact Name: Jon Becker
Contact Email: Jonbecker@aol.com
Description: Preliminary interaction regarding future mapping of springs in Cherokee Marsh (Madison, WI) using single-engine airplane. They seek a better understanding of the location of springs in the marsh and impact of those springs on the hydroecology of the wetland. Ultimately, we would like to work with FOCM to use this information to guide restoration of the wetland and protectection of recharge ares feeding the springs and fens of Cherokee Marsh.

Event Date

Description

We worked closely with the unmanned aircraft division of the Federal Aviation Administration in order to obtain a Certification of Authorization (COA) for use of the unmanned aerial vehicle. Due to the nature of our work, the FAA classifies our vehicle as a "public" aircraft. Consequently, the FAA required us to obtain a COA. The COA permits unmanned aircraft on the basis of air worthiness, planned flight locations and other factors. The process took 6-months and is now complete.
Event Date: August 2007 – February 2008
Permit Identification: 2007-AHQ-46

Event Date

Description

Description: We obtained a permit from the Federal Communications Commission for use of the unmanned aerial vehicle transmitter.
Event Date: January 2008 – April 2008
Permit Identification: Federal Communications Commission Experimental Radio Station Construction Permit and License # 0049-EX-PL-2008 (WE2XOK Call Sign)

Event Date

Description

Description: We worked with a local flight school to obtain a ground-school private pilot certificate in order to have clearance for use of our unmanned aerial vehicle.
Event Date: February and March 2008
Permit Identification: Completion of FAA Private Pilot written exam and clearance for a third class private pilot medical certification

Event Date

Journal Articles & Other Publications

Publication Type Peer-Reviewed Journal Article/Book Chapter

Title Ground-based thermal imaging of groundwater flow processes at the seepage face

Author(s)	Richard S. Deitchman, Steven P. Loheide II
Publication/Publisher	Geophysical Research Letters
Year Published	
Volume & Number	
Number of Pages	
Description	Accepted pending minor revisions on 5/11/2009
Any Additional Citation Information	

Publication Type	Newsletter/Periodical
Title	UW research taking a birds-eye view of groundwater discharge
Author(s)	UW-Madison News
Publication/Publisher	UW-Madison
Year Published	2007
Volume & Number	
Number of Pages	
Description	Online UW News Article on project and other WRI-funded projects (8/14/2007)
Any Additional Citation Information	

Publication Type	
Title	Simulating the impacts of climate change on the temperature of a Driftless Area trout stream using remotely sensed thermographic profiles and in-stream temperature histories
Author(s)	Richard S. Deitchman, Steven P. Loheide II
Publication/Publisher	
Year Published	
Volume & Number	
Number of Pages	
Description	in preparation
Any Additional Citation Information	

Other Project Support

Source	College of Engineering Start Up Funds; Wisconsin Alumni Research Foundation
Dollar Value	$22,000
Description	Financial support for thermal infrared camera, single-engine airplane flight time, unmanned aerial vehicle construction (parts and student labor), HOBO in-stream temperature loggers at East Branch Pecatonica field sites, installation and downloading of HOBO loggers by a student not involved in the project (summer 2007).
Start Date	7/1/2007
End Date	8/1/2008

Partners

Name/Organization	Eric Booth
Affiliation	East Branch Pecatonica River Restoration Observatory
Affiliation Type	Other
Email	egbooth@wisc.edu
Description	Multi-disciplinary team of researchers investigating hydrology, ecology, geomorphology, biogeochemistry and engineering at two restoration sites on the East Branch Pecatonica River. Researchers: -Eric Booth, Ph.D. Student, Center for Limnology/Civil and Environmental Engineering -Prof. Steve Loheide, Civil and Environmental Engineering -Prof. Emily Stanley, Center for Limnology -Prof. Jim Knox, Department of Geography Land Managers: -Steve Richter, The Nature Conservancy -Bob Hansis, Wisconsin Department of Natural Resources -Katie Abbott, Military Ridge Prairie Heritage Area Website: http://hydroecology.cee.wisc.edu/EBP/index.htm

Presentations & Public Appearances

Title	The use of an unmanned aerial vehicle for mapping spring and diffuse groundwater discharge to streams
Presenter(s)	Richard S. Deitchman
Presentation Type	Seminar
Event Name	Department of Civil and Environmental Engineering Water Resources Engineering and Environmental Fluid Mechanics Seminar
Event Location	Engineering Hall, Madison, WI
Event Date	12/13/2007
Target Audience	University students
Audience Size	20
Description	45 minute talk to Water Resources Engineering group on the project methdology.

Title	Thermal remote sensing detection of groundwater discharge to streams
Presenter(s)	Steven P. Loheide II
Presentation Type	Professional meeting
Event Name	Geological Society of America (GSA) 2007 Annual Meeting
Event Location	Denver, Colorado
Event Date	10/29/2007

Target Audience	Scientific audience
Audience Size	120
Description	Invited presentation for session titled "Innovation and New Technologies for Measuring and Characterizing Groundwater-Surface Water Interaction"

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Title	Thermal remote sensing of stream temperature - a tool for mapping springs
Presenter(s)	Richard S. Deitchman, Steven P. Loheide II
Presentation Type	Other
Event Name	Friends of Allen Creek Watershed monthly meeting
Event Location	Koshkonong Town Hall, Ft. Atkinson, Wisconsin
Event Date	9/9/2008
Target Audience	Public
Audience Size	20
Description	Public presentation on thermal remote sensing research and planned UAV flights at Allen Creek site

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Title	Using thermal remote sensing in Wisconsin - a way to help administer 2003 WI Act 310?
Presenter(s)	Richard S. Deitchman
Presentation Type	Other
Event Name	Meeting with WDNR representatives from the Water Use Section
Event Location	WDNR, S. Webster Street, Madison, Wisconsin
Event Date	11/12/2008
Target Audience	State government agency
Audience Size	7
Description	Presentation to representatives from the Wisconsin DNR on the methodology and how thermal remote sensing may be used for statewide spring inventories

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Title	The use of thermal remote sensing for mapping spring and diffuse groundwater discharge: applications to Wisconsin groundwater law and management
Presenter(s)	Richard S. Deitchman
Presentation Type	Seminar
Event Name	University of Wisconsin - Madison Department of Urban and Regional Planning
Event Location	Music Hall, Madison, Wisconsin
Event Date	12/11/2008
Target Audience	University students
Audience Size	25
Description	Presentation to students in a water policy course on the policy implications of the methodology

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Title	Characterization of groundwater flux using ground-based thermal remote sensing at the seepage face
Presenter(s)	Richard S. Deitchman, Steven P. Loheide II
Presentation Type	Professional meeting
Event Name	American Water Resources Association - Wisconsin Section 2009 Annual Meeting
Event Location	Stevens Point, Wisconsin
Event Date	3/5/2009
Target Audience	Mixed
Audience Size	50
Description	Presentation on ground-based thermal remote sensing work at the 2009 AWRA meeting; won "Best Student Platform" presentation award

Students & Post-Docs Supported

Student Name	Richard Deitchman
Campus	University of Wisconsin-Madison
Advisor Name	Steven Loheide
Advisor Campus	University of Wisconsin-Madison
Degree	Masters
Graduation Month	May
Graduation Year	2009
Department	Gaylord Nelson Institute for Environmental Studies
Program	Environment and Resources
Thesis Title	Thermal remote sensing of stream temperature – applications to hydrogeology and water resources policy in Wisconsin
Thesis Abstract	Thermal remote sensing is increasingly utilized as a tool in hydrology because it is easily-transferable, can provide high-resolution, synoptic views of water resource issues and may provide answers to difficult research questions. Thermal infrared radiation is generally considered to have a wavelength between 3.5-20 μm. Commercial thermal infrared sensors typically detect radiation in the 7.5-13 μm wavebands. The reduced cost of thermal imaging cameras now provides a cost-effective method for imaging to be used for stream temperature and groundwater discharge analysis (Cardenas et al. 2008, Loheide and Gorelick 2006, Torgerson et al. 1999). The temperature of groundwater is relatively constant through time whereas surface water temperature varies on seasonal and diurnal cycles. This thermal signature allows groundwater discharge to be located at the surface with thermal imaging. The purpose of this research is to investigate the use of thermal remote sensing for water resources science and policy in the State of Wisconsin. Science-based management is essential to the future of Wisconsin's water resources. Wisconsin is very progressive nationally in water resources policy; Wisconsin 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. This project includes three case studies on the use of thermal remote sensing along with a chapter detailing the policy implications of the new methodologies for the State of Wisconsin. There is no existing method to image groundwater processes along a seepage face. Thus, it is often difficult to quantify the magnitude and spatial variability of groundwater flux across this interface. Ground-based thermal imaging was employed in the University of Wisconsin-Arboretum as a new, transferable, non-invasive method that uses heat as a natural tracer to image spatially-variable

groundwater flow processes and distinguish between focused and diffuse groundwater discharge to the surface. For the first time, the work demonstrates that thermal remote sensing of groundwater at the seepage face provides indirect imaging of both the saturated zone-unsaturated zone transition and groundwater flux at the centimeter scale, offering further insight into flow heterogeneity.
Airborne thermal remote sensing from a single-engine airplane was used to collect thermal infrared data that validated a one-dimensional stream temperature model of the East Branch Pecatonica River. Model simulations of various climate change scenarios suggest that stream temperatures may reach critical thresholds of mortality for brook trout (Salvelinus fontinalis) and brown trout (Salmo trutta). The work uses an existing, freely-available one-dimensional stream temperature model calibrated with longitudinal profiles of stream temperature created from four thermal imaging flights and data from in-stream loggers. It demonstrates that thermal infrared data can greatly assist stream temperature model validation due to its high spatial resolution, can be used to pinpoint spatial heterogeneity in groundwater inflow to streams and that stream temperature models considering climate change are important for fisheries management.
Data collected from an unmanned aerial vehicle is used to show the potential use of thermal remote sensing for administration of 2003 Wisconsin Act 310. Among other measures, Act 310 regulates the influence of high-capacity pumping wells on springs. Springs are defined as "[areas] of concentrated groundwater discharge occurring at the surface of the land that result in a flow of at least one cubic foot per second at least 80 percent of the time." Currently, information about the location and flow of springs is limited on a statewide basis. Unmanned aerial vehicles may be employed to collect thermal imagery for the mapping of springs. However, numerous technical and regulatory barriers curtail the use of unmanned aerial vehicles for data collection on a statewide basis. This thesis highlights the value of unmanned aerial vehicles and discusses the policy, regulatory and technical barriers to implementation.

Other Activities

Description	Badger Ridge Middle School science education program. 6th grade students come to the department to learn about careers in environmental engineering. Loheide and Deitchman present an inquiry-based unit on groundwater and its importance in the state.
Event Date	5/27/2008