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WR14R003

HYDRAULIC IMPACTS OF THE LOSS OF WISCONSIN'S WINTER ON SURFACE WATER - GROUNDWATER INTERACTIONS

Steven P. Loheide
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2014

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Hydraulic Impacts of the Loss of Wisconsin's Winter on Surface Water – Groundwater Interactions

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PROJECT SUMMARY

Title: Hydraulic Impacts of the Loss of Wisconsin's Winter on Surface Water – Groundwater Interactions

Project I.D.: WR14R003

Investigator(s): Steve Loheide, Associate Professor, Civil and Environmental Engineering;
Kim Scherber, Graduate Research Assistant, Civil and Environmental Engineering

Period of Contract: July 1, 2014 – June 30th, 2016

Objectives: This study seeks to answer three research questions: I) What effects do ice cover regimes have on surface water–groundwater interactions across a range of stream types and field conditions? II) What is the magnitude of ice formation-induced changes to surface water–groundwater interactions and how has climate change altered the surface water–groundwater exchange? III) How do ice cover regimes vary across stream sizes and how have these regimes changed over a period of historic observations?

Methods: To answer these questions, five field sites near current United States Geological Survey (USGS) stream gauges were chosen on rivers of varying drainage size and ice cover regime in southern Wisconsin for observation and analysis. The field sites listed from smallest to largest watershed size were the East Branch Pecatonica near Barneveld, Black Earth Creek at Black Earth, the Fox River at Waukesha, the Sugar River near Brodhead, and the Wisconsin River at Muscoda. To answer research question I, 3 to 4 piezometers were installed at each field site to understand surface water-groundwater interactions during ice formation events. To answer research question II, groundwater flow modeling was performed to simulate the movement of water in the subsurface during ice formation events. Results from the field models were used to develop archetype models to simulate surface water–groundwater interactions for different ice cover regimes, sediment types, and groundwater inflow rates. To answer research question III, a historical analysis was performed to quantify surface ice advances using field site relationships developed from the 2015-2016 winter season for each site and applied to its historical USGS stream stage data.

Results and Discussion: All sites experienced at least one ice formation event during the 2015-2016 field season despite being the 5th warmest winter during the historical study period. The East Branch Pecatonica, Fox, Sugar, and Wisconsin rivers all had similar average ice induced stage increases of approximately 0.11 m while Black Earth Creek had the smallest stage increase of 0.05 meters. This difference in average peak height is likely due to a higher percentage of groundwater contributing to Black Earth Creek's base flow, which prevents water from freezing extensively [*Field & Graczyk, 1990*]. The historical analysis revealed a consistent pattern in average stage increase due to ice formation in which streams with smaller watersheds (East Branch Pecatonica, Black Earth Creek, and Fox River) have smaller stage increases due to ice formation compared to the Sugar and Wisconsin River, which have nearly 2 to 4 times greater stage increases. This historical pattern was not observed for the 2015-2016 data likely due to warm wintertime temperatures that did not encourage as substantial ice formation.

For the 2015-2016 study period, Black Earth Creek had the fewest number of ice advances with only one ice event while the Wisconsin River had the most with 17 ice advance events. Historical ice advance data trends with watershed size with the smallest watershed, excluding Black Earth Creek, having the fewest ice advances (7 ice events) while the Wisconsin River had the most (31 ice events) (see Figure 5). Figure 4 shows ice formation advance totals by year for each field site and shows a general trend of years with the fewest overall ice advances were years with warmer average wintertime temperatures.

As can be seen in Figures 6-10, the piezometers at all field sites indicate that the subsurface aquifer interacts with ice formation induced stage increases in the stream as water temperature approaches 0° C. These fluctuations in the shallow aquifer pressure head are caused by an increase in stream stage, which reduces the hydraulic gradient towards the stream as well as reduces groundwater discharge to the stream. If the hydraulic gradient toward the stream is very shallow, the potential exists for hyporheic exchange to occur, as described by *Sawyer et al.* [2009], as surface water moving in and out of the aquifer caused by changing levels in river stage.

Pressure head fluctuations gradually attenuate as the ice advance signal propagates farther into the subsurface aquifer and away from the stream. Percent attenuation varies across field sites, with the most attenuation occurring at the Fox River and the least at Black Earth Creek. Differences in percent attenuation are dependent upon hydraulic conductivity of the aquifer sediment.

Conclusions: This study analyzed the similarities and differences of hydrological behaviors of ice formation advances in select streams in Wisconsin and their corresponding impact on the shallow, subsurface aquifer. The results found that all streams studied were capable of generating ice formation induced stage peaks which caused reductions in the hydraulic gradient in the subsurface aquifer as far away as 51 meters from the stream. This reinforces *Weber et al.*'s [2013] work and suggests that the riparian subsurface aquifer is more dynamic than commonly acknowledged in cold weather environments and it may play an important role in riparian biogeochemical processes such as nutrient cycling depending upon the slope of its hydraulic gradient. This study also conducted a historical analysis and found that winters with higher mean air temperatures also correlated to winters with less river ice advances. With Wisconsin's wintertime temperature predicted to increase 4-9° F by the middle of the century, all streams that experience freezing under current climatic conditions and their immediate aquifers will likely be affected.

Related Publications: None.

Key Words: Wisconsin rivers, climate change, dynamic ice formation, surface water – groundwater interactions

Funding: WR14R003

INTRODUCTION

Wisconsin's climate is changing. Over the past 60 years, statewide average yearly temperatures increased by 1.1° F while average yearly wintertime temperatures increased by 2.5° F, with temperatures warming the fastest at night [*Kucharik et al*., 2010]. Using downscaled global circulation models, WICCI [2011] predicts that by the middle of the century Wisconsin's statewide annual average temperature will increase 4-9° F while winter temperatures will increase 5-11° F. This wintertime warming will likely trigger shorter, milder winters [*Magnuson et al*., 2003; *Kucharik et al*., 2010], which will further disturb temperature dependent climatological processes such as snow cover duration [*Notaro et al*., 2010] and lake ice duration [*Magnuson et al.,* 2003]. Of these records, historic lake ice cover has been particularly important in documenting long-term changes of climate as well as short-term climate variability since it often has the longest period of record compared to other climatological datasets [*Kucharik et al*., 2010; *Magnuson et al*., 2000]. *Magnuson et al.* [2003] reported that from 1855 to 2010, Lake Mendota experienced 29 less days of ice cover while Lake Menona experienced 35 less days of ice cover due to initial dates of freezing occurring later in the winter and lake ice breakup occurring earlier.

Despite the importance of these hydrological records, Wisconsin's other long-term surface water dataset – rivers– have been neglected in regards to their historical climatological significance. Although there has been some research describing changes in historical ice cover on large rivers in the northern hemisphere [*Magnuson et al., 2000*; *Prowse and Bonsal*, 2004], changes in Wisconsin's statewide river ice regimes have never been documented. Furthermore, the impact of river ice on the immediate subsurface aquifer, as discovered by *Weber et al.* [2013], has never been investigated to understand if the peaks observed in the potentiometric surface caused by surface ice formation extend to rivers of larger drainage size or if this mechanism is unique for small streams only. If this novel mechanism proves to be universal for all rivers capable of producing significant freeze events, the hydraulic gradient towards these streams will be reduced during freeze events with the possibility of hyporheic exchange [*Weber et al.*, 2013], which is the mixing of surface and groundwater in the shallow subsurface aquifer. During hyporheic exchange, the boundary condition: stream stage, will overcome the normal hydraulic gradient by a rapid increase in stage due to shear stress created from ice formation [*Prowse and Beltaos*, 2002]. Under hyporheic exchange, biogeochemical processes that control nutrient cycling and other water quality processes [*Stanford and Ward*, 1988; *Boulton et al*., 1998; *Brunke and Gonser*, 1997; *Findlay*, 1995; *Krause et al*., 2010; *Gu et al.*, 2012] would not only occur at times of flooding [*Chen and Chen*, 2003] during the spring or summer, but also occur during the winter due to river ice formation [*Weber et al.*, 2013].

This study seeks to answer three research questions: I) What effects do ice cover regimes have on surface water–groundwater interactions across a range of stream types and field conditions? II) What is the magnitude of ice formation-induced changes to surface water–groundwater interactions and how has climate change altered the surface water–groundwater exchange? III) How do ice cover regimes vary across stream sizes and how have these regimes changed over a period of historic observations?

To answer these questions, five field sites near current United States Geological Survey (USGS) stream gauges were chosen on rivers of varying drainage size and ice cover regime in southern Wisconsin for observation and analysis. To answer research question I, 3 to 4 piezometers were installed at each field site to understand surface water-groundwater interactions during ice formation events. To answer research question II, groundwater flow modeling was performed to simulate the movement of water in the subsurface during ice formation events. Results from the field models were used to develop a suite of archetype models to simulate surface water–groundwater interactions for a range of different field conditions. To answer research question III, a historical analysis was performed for each site to quantify surface ice advances using field site relationships developed from the 2015-2016 winter season and applied to its historical USGS stage data.

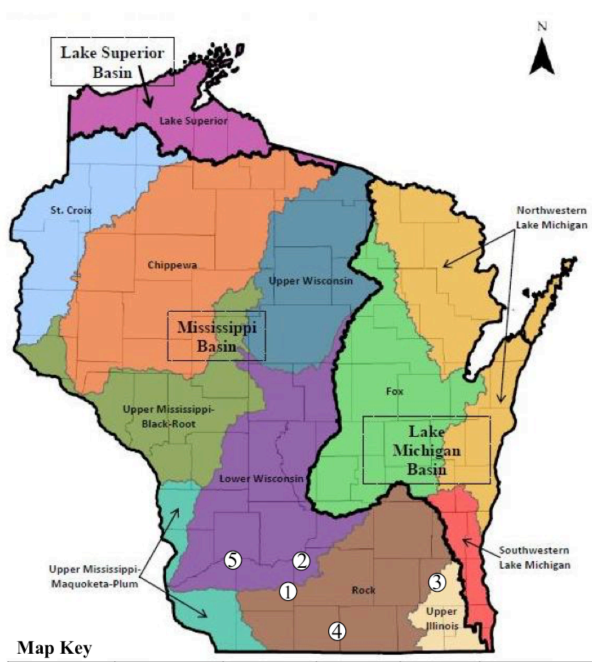
PROCEDURES AND METHODS

Collection of field data

The preliminary criteria for selecting field sites for this analysis were that they had to have at least 27 years of continuous electronic USGS stage data, be within two hours of driving from Madison, and be located on easily accessible, public land. From potential sites that matched this preliminary screening, 5 sites were chosen that relatively uniformly spanned a range of watershed size with the East Branch Pecatonica site from *Weber et al.'s* [2013] study being the smallest to the Wisconsin River, the largest. Basic field site descriptions can be referenced in Table 1 and site locations relative to their respective drainage basin is shown in Figure 1.

Table 1. Field site descriptions

Site	USGS Hydrologic Unit	River Basin	Drainage area (km^2)	Average discharge (m^3/s)
East Branch Pecatonica	NA	Rock River Basin	13	0.12
Black Earth Creek	07070005	Wisconsin River Basin	118	1.36
Fox River	05543830	Illinois-Fox River Basin	326	2.55
Sugar River	05436500	Rock River Basin	1355	9.37
Wisconsin River	05407000	Wisconsin River Basin	26936	238.43



Map Key

Number	1	2	3	4	5
Site	East Branch Pecatonica	Black Earth Creek	Fox River	Sugar River	Wisconsin River

Figure 1. Field site locations with watershed location (source: Great Lakes Legal Foundation)

In the fall of 2014, 3-4 piezometers were installed to a depth of 2.5-3.5 in transect perpendicular to the river with the first well sited at the stream bank, the second approximately 2 meters from the stream bank, the third approximately 10 meters from the stream bank, and the final well (at select sites) at the edge of the floodplain (or where the public property ended). Piezometers were installed by hand augering and placing a PVC casing with a 20 cm screen in the borehole; when the sediment was too coarse for auger use, a drive point well with a 91 centimeter screen was installed. In each piezometer, a HOBO U20L-004 (± 2.0 cm maximum error) or a HOBO U20-001-04 (± 1.0 cm maximum error) water level logger was installed approximately 20 centimeters from the bottom of the well to record the pressure of the water column in each well every 15 minutes. An additional pressure transducer recording atmospheric pressure every 15 minutes was installed in the well farthest from the river, just below the ground surface. Hand measurements with a water level tape were taken monthly to verify water column height.

In the fall of 2015, integrated water level loggers (HOBO U20-001-04) with temperature reading capabilities (± 0.44° C error) were installed in each river, in transect with the piezometers, with a stream depth of at least 2.5 feet. In addition, a Bushnell X-8 trail camera (model 119327) was installed at each site and programmed to take photos every 15 minutes to capture shelf ice formation on the opposite bank of the river. Surveying was completed using a Topcon RTK-GPS, model GR5 and an auto level with rod.

Analysis of field data

All pressure transducer data was processed using MATLAB 2016a. Data collected from onsite pressure transducers was used to calculate hydraulic head, hydraulic gradient, and stage deviations from steady state conditions before a significant ice formation event. Stage deviations shown in this paper was chosen for the week of 01/14/2016 to 01/27/2016 and base conditions were represented by those prevailing on 01/15/2016 for the East Branch Pecatonica, Black Earth Creek, Fox River, and Sugar and from from 12/16/2015 00:00 to 12/16/2015 06:00 for the Wisconsin River.

Historical analysis

Number of ice advances was chosen as the parameter of interest for the historical analysis. We defined an ice advance as a significant stage increase, which will be referred to as peaks, when ice formation occurs under freezing conditions with no rain. Ice cover duration was not chosen as a historical analysis parameter due to the presence of a suspended ice shelf, as commonly seen at the Fox, Sugar and Wisconsin river sites. With a suspended ice shelf, the ice is visually present but a majority of the ice shelf is unconnected with the river stage and therefore has little observed influence on discharge.

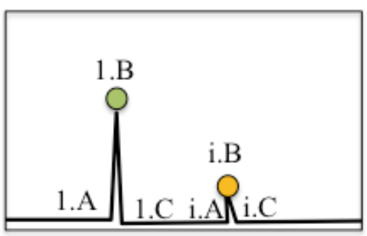


Figure 2. Naming convention for ice advance peaks for the historical analysis. The first character denotes whether the peak is a significant ice advance (number) or insignificant ice advance/non-ice event (small roman numeral) and consecutively tallies these events throughout the analysis period. The second character signifies the ice advance phase. Letter A represents time immediately before stage increase, letter B the time of peak maximum, and letter C the time which stage height approaches stage height at letter A.

A MATLAB algorithm was developed to identify peaks using a series of 4 consecutively applied criteria, based off of air temperature, stage, and water temperature thresholds derived from the 2015-2016 field data during known, visual ice formation advances. The first criteria utilized a five-point moving average to smooth data to minimize the effects of transducer noise, which could be inadvertently identified as ice-induced peaks. The peaks that pass this filter are shown with hollow circles. Because ice only forms under cold temperatures, we removed from consideration potential peaks occurring on days when the daily low temperature was above a threshold when ice formation is not expected. Days that amassed rainfall were also removed from consideration with the additional criteria that significant peaks that occur 5 days after a rain event of 1.5 centimeters were also disregarded at the Wisconsin River site due to its large watershed. The peaks that pass this filter are shown with red filled circles. The third filter is a stream-specific, ice formation stage threshold to help identify "significant" ice events. The stage peaks that are equal or larger than the specified threshold that pass this filter are shown with yellow circles. Finally, there is a maximum water temperature threshold and only peaks that occur at stream temperatures below this threshold are retained as potential ice-related peaks. These peaks are shown with green circles and indicate definitive instances of ice advance. The last threshold is only used in the 2015-2016 winter season since insitu water temperature data only existed for that year. The USGS has limited water temperature data at Black Earth

Creek and the Wisconsin River but their water temperature data usually only fell to 1° C during the same time period that our field stream temperature observations reached 0.1° C, so that data was not used. Because water temperature data was not consistently available from the long-term USGS records, only the first three thresholds were used to identify ice advances in our historical analysis.

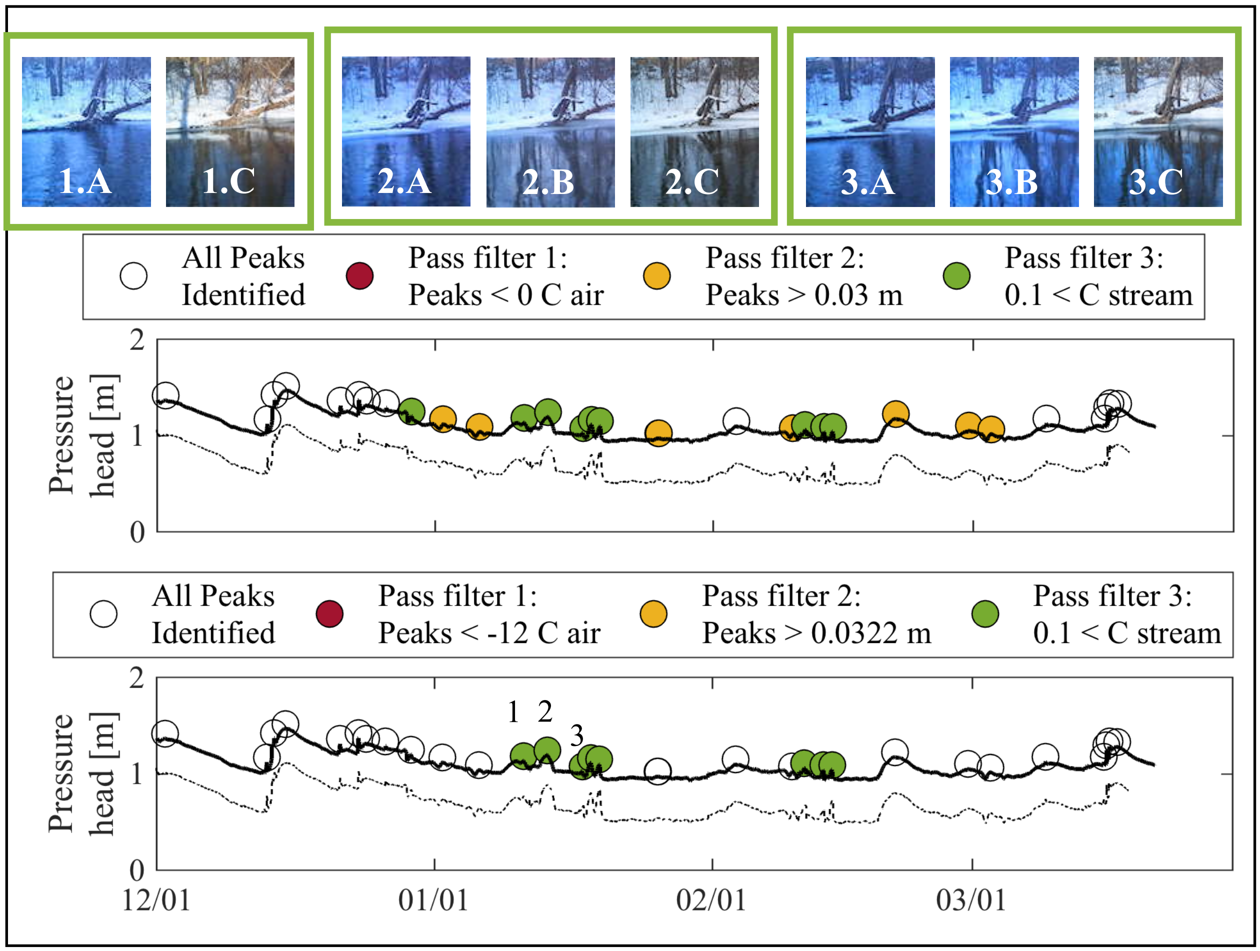


Figure 3. Fox river historic analysis

Air temperature, stage, and water temperature thresholds were determined individually for each site. First, observable ice formation advances were documented from the trail camera. Ice events that only prompted ice growth around river debris in very shallow areas were not counted as a significant ice event. For each ice significant formation event, pictures were labeled as before, during, and after the ice formation event. Details the photo cataloguing label convention can be referenced in Figure 2 and an example of photo verification of ice advances can be seen in Figure 3. After photo verification, thresholds were determined by a two-step process. The first step sought to identify all definitive ice advance events by setting air temperature to 0 degrees Celsius (criteria 2), the stage threshold to 0.03 m (criteria 3), and conservatively setting the water temperature to 0.1° C (criteria 4). The first stage plot in Figure 3 is a condensed example for this preliminary analysis for the Fox River site. Reduction of the occurrence of false positive identification of ice formation peaks was accomplished in the second step by lowering air temperature until yellow and red circles were eliminated whilst retaining green circles (see second stage plot in Figure 3). Stage thresholds were determined as the smallest stage peak increase of the peaks classified as green circles. Site thresholds can be referenced in the results section in Table 2.

RESULTS AND DISCUSSION

As shown in Figures 5 and Table 3, all sites experienced at least one ice formation event during the 2015-2016 field season despite being the 5th warmest winter during the historical study period. The East Branch Pecatonica, Fox, Sugar, and Wisconsin rivers all had similar average ice induced stage increases of approximately 0.11 m while Black Earth Creek had the smallest stage increase of 0.05 meters. This difference in average peak height is likely due to a higher percentage of groundwater contributing to Black Earth Creek's base flow, which prevents water from freezing extensively [*Field & Graczyk, 1990*]. The historical analysis revealed a consistent pattern in average stage increase due to ice formation in which streams with smaller watersheds (East Branch Pecatonica, Black Earth Creek, and Fox River) have smaller stage increases due to ice formation compared to the Sugar and Wisconsin River, which have nearly 2 to 4 times greater stage increases (see Figure 5 and Table 3). This historical pattern was not observed for the 2015-2016 data likely due to warm wintertime temperatures that did not encourage as substantial ice formation.

Table 2. Air temperature, stage, and water temperature thresholds

Site	Filter 1: Maximum air temperature threshold, °C	Filter 2: Minimum stage for classification as a significant ice formation event, [m]	Filter 3: Maximum water temperature for ice advance, °C
East Branch Pecatonica	- 16	0.0306	0.3
Black Earth Creek	- 19	0.0542	0.1
Fox River	- 12	0.0322	0.1
Sugar River	- 12	0.0383	0.1
Wisconsin River	- 9	0.0346	0.1

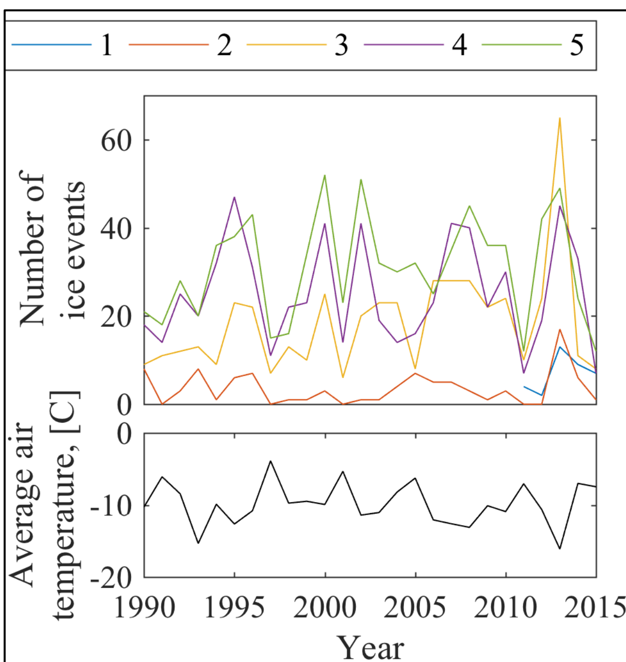


Figure 4. Number of ice events versus average air temperature. Sites are ranked by increasing drainage area. E.g. 1 = East Branch Pecatonica, 5 = Wisconsin River

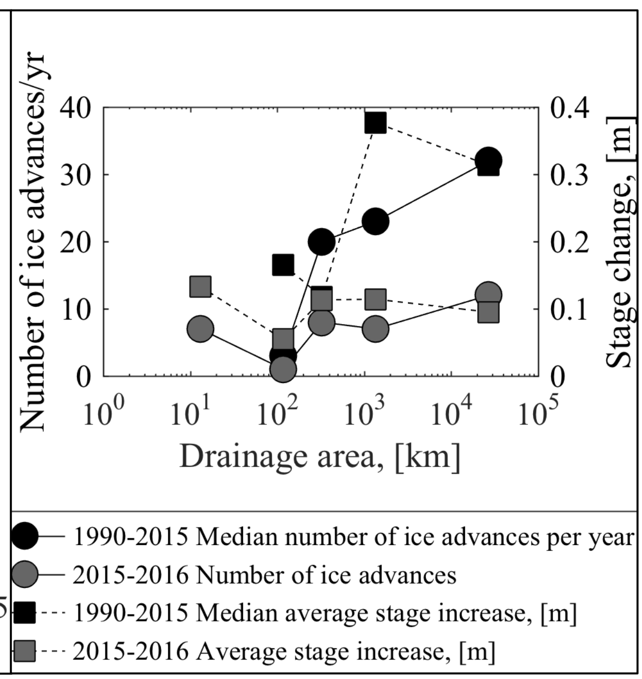


Figure 5. Drainage area versus median historical number of ice advances per year and median historical stage increase

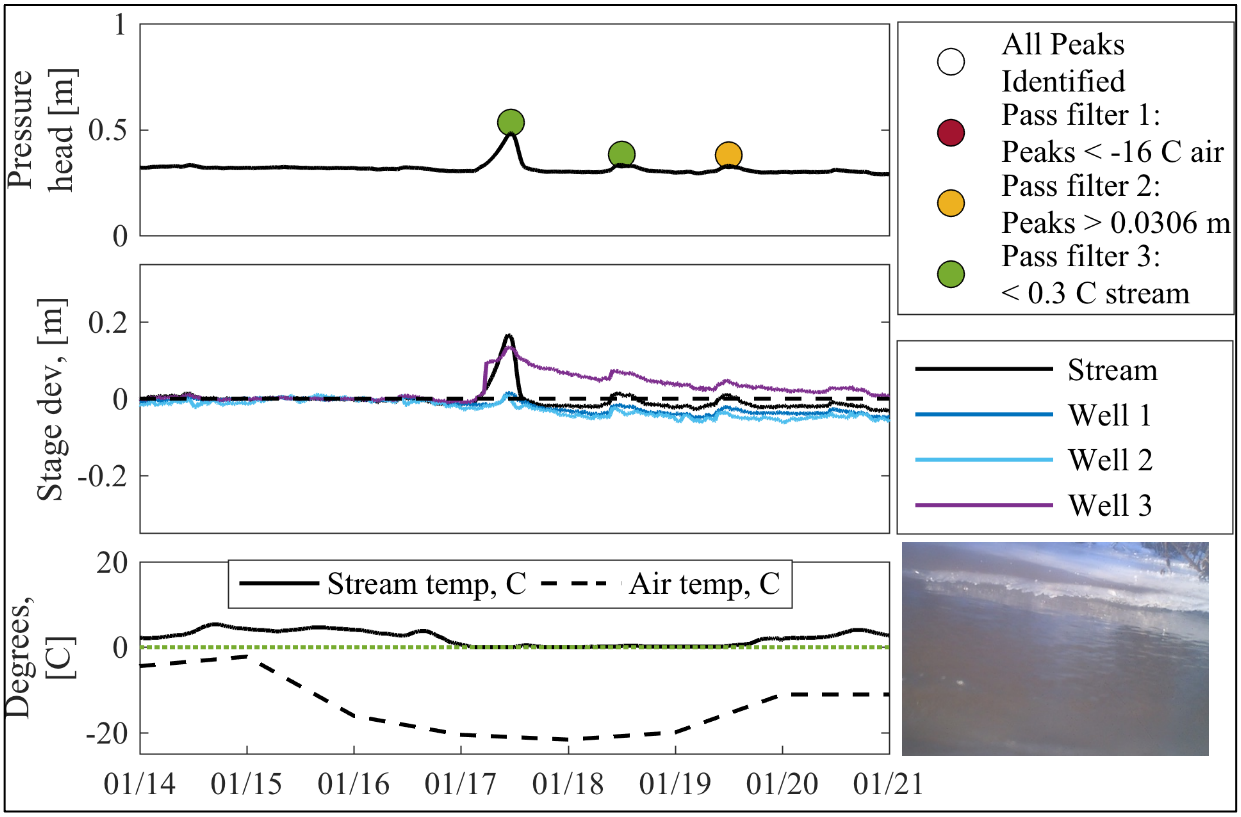


Figure 6. EBP pressure head, stage deviation, and temperature for 01/14/2016 - 01/21/2016

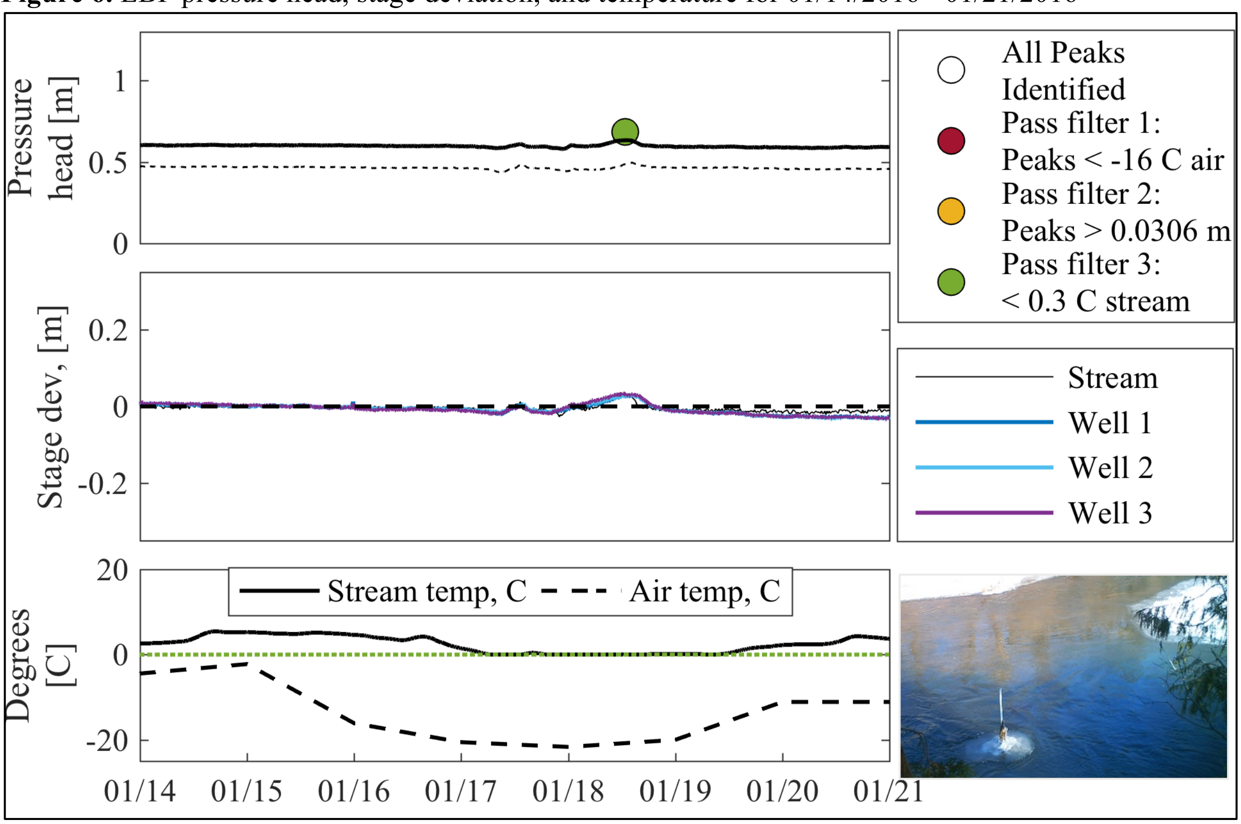


Figure 7. BEC pressure head, stage deviation, and temperature for 01/14/2016 - 01/21/2016

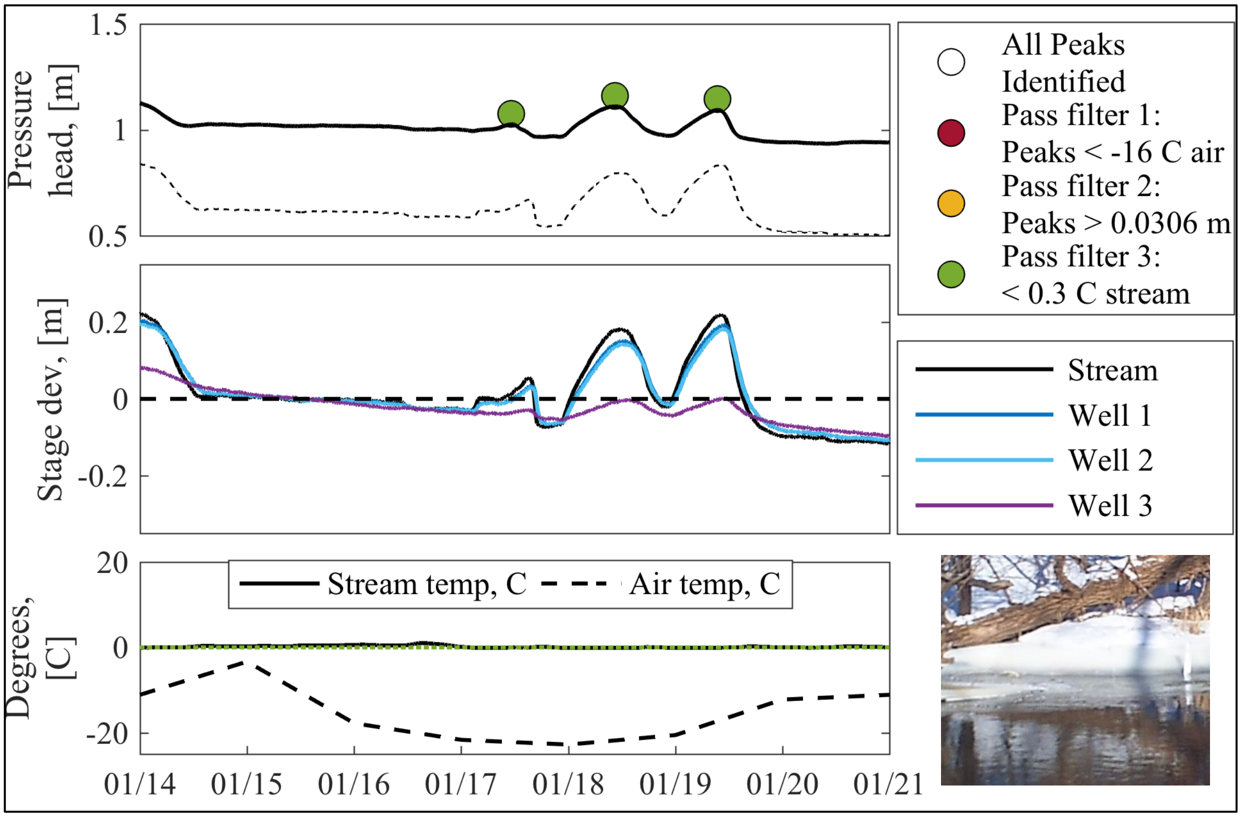


Figure 8. Fox River pressure head, stage deviation, and temperature for 01/14/2016 - 01/21/2016

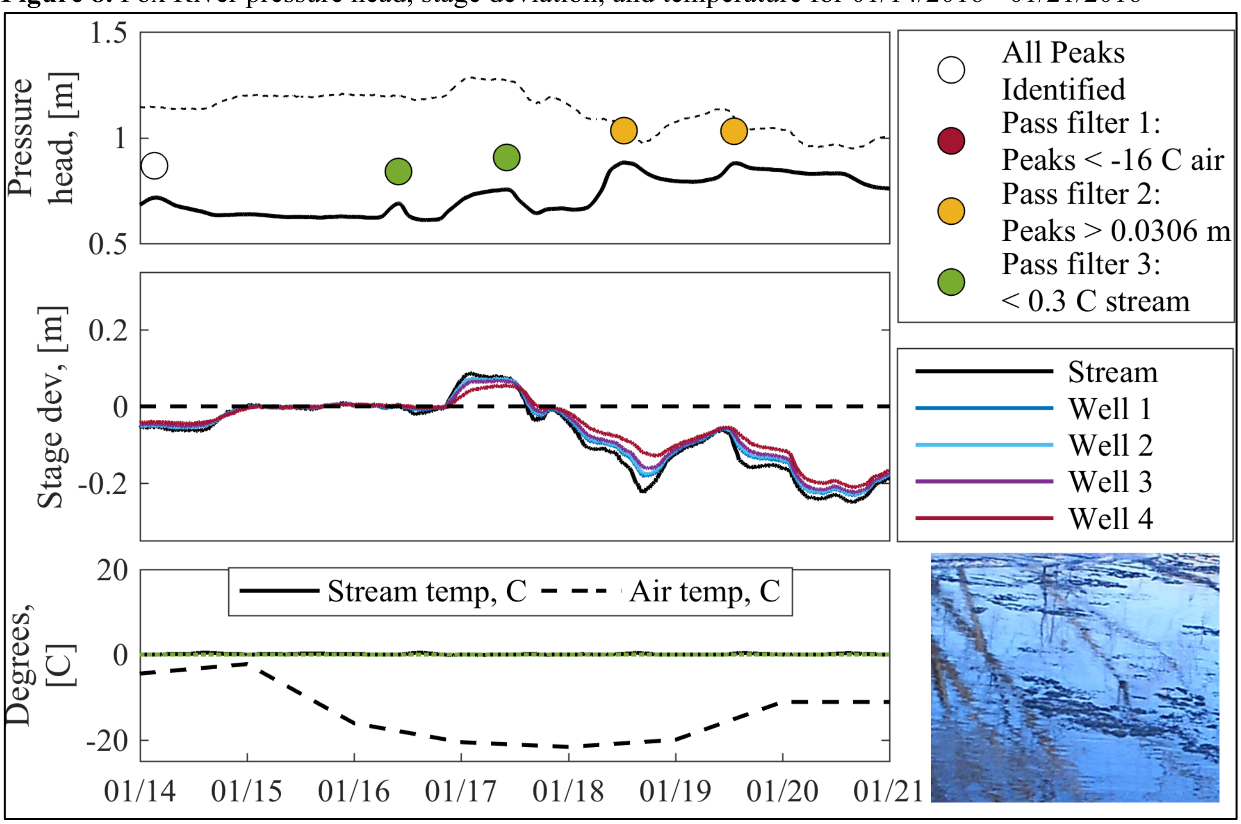


Figure 9. Sugar River pressure head, stage deviation, and temperature for 01/14/2016 - 01/21/2016

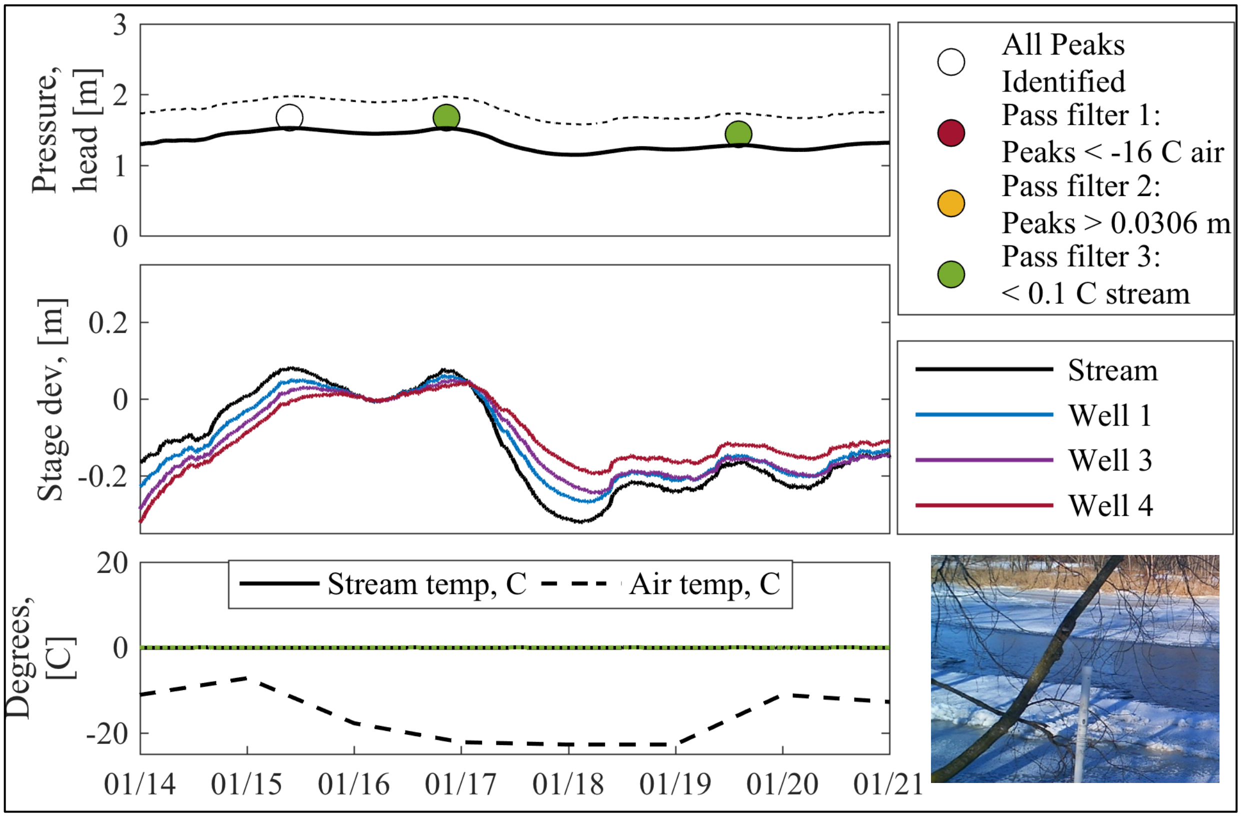


Figure 10. Wisconsin River pressure head, stage deviation, and temperature for 01/14/2016 -01/21/2016

For the 2015-2016 study period, Black Earth Creek had the fewest number of ice advances with one ice event while the Wisconsin River had the most with 17 ice advance events. Historical ice advance data trends with watershed size with the smallest watershed, excluding Black Earth Creek, having the fewest ice advances (7 ice events) while the Wisconsin River had the most with 31 ice events (Figure 5; Table 3). Figure 4 shows ice formation advance totals by year for each field site and shows a general trend of years with the fewest overall ice advances were years with warmer average wintertime temperatures.

Table 3. Field data and historical analysis results

Site	**Number of ice formation advances for 2015-2016**	**Stage increase due to ice formation for 2015-2016, [m]**	**Average number of ice formation advances per year for 1990-2015**	**Median number of ice formation advances per year for 1990-1995**	**Average stage increase due to ice formation for 1990-2015, [m]**	**Median stage increase due to ice formation for 1990-2015, [m]**
East Branch Pecatonica	7	0.13	NA	NA	NA	NA
Black Earth Creek	1	0.05	4	3	0.18	0.17
Fox River	8	0.11	19	20	0.13	0.12
Sugar River	7	0.11	26	23	0.36	0.38
Wisconsin River	12	0.10	31	32	0.33	0.31

As can be seen in Figures 6-10, the piezometers at **all** field sites indicate that ice formation induced stage increases in the stream as water temperature approaches 0° C correspond with groundwater fluctuations in the shallow aquifer. These groundwater fluctuations in the shallow aquifer are caused by an increase in the stream stage, which reduces the hydraulic gradient towards the stream as well as reduces groundwater discharge to the stream. If the hydraulic gradient toward the stream is very shallow, the potential exists for hyporheic exchange to occur, as described by *Sawyer et al.* [2009], as surface water moving in and out of the aquifer caused by changing levels in river stage.

Pressure head fluctuations in the subsurface aquifer gradually attenuate as the ice advance signal propagates farther away from the stream. In Table 4, percent attenuation varies across field sites, with the most attenuation occurring at Fox River and the least at Black Earth Creek. Differences in percent attenuation are dependent upon hydraulic conductivity of the aquifer soils. Since both the maginitude of the ice formation induced stream stage and they hydraulic conductivity of the aquifer tends to increase with stream stage, the magnitude of alteration in stream aquifer interactions increases with increasing river size.

Table 4. Percent stage attenuation for 01/14/2016 to 01/21/2016 ice peaks

	EBP	**BEC**	**Fox River**	**Sugar River**	**Wisc. River**
Well 1	91%	22%	16%	15%	21%
Well 2	95%	19%	22%	16%	NA
Well 3	20%	17%	100%	24%	38%
Well 4	NA	NA	NA	51%	51%

CONCLUSIONS

This study analyzed the similarities and differences of hydrological behaviors of ice formation advances in select streams in Wisconsin and their corresponding impact on the shallow, subsurface aquifer. The results found that all streams studied were capable of generating ice formation induced stage peaks which caused reductions in the hydraulic gradient in the subsurface aquifer as far away as 51 meters from the stream. This reinforces *Weber et al.*'s [2013] work and suggests that the riparian subsurface aquifer is more dynamic than commonly acknowledged in cold weather environments and it may play an important role in riparian biogeochemical processes such as nutrient recycling depending upon the slope of its hydraulic gradient. This study also conducted a historical analysis and found that winters with higher mean air temperatures also correlated to winters with less river ice advances. With Wisconsin's wintertime temperature predicted to increase 4-9° F by the middle of the century, all streams capable of freezing and their immediate aquifers will likely be affected.

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Image: Great Lakes Legal Foundation. http://greatlakeslegalfoundation.org/2013/03/04/agencies-seeking-comments-guidelines-wetland-mitigation/ web. 26 August 2016.

APPENDIX A

PRESENTATIONS

Scherber, K; and SP Loheide II. "Hydraulic Impacts of Wisconsin's Winter On Surface Water – Groundwater Interactions". Poster presented at: American Water Resources Association Wisconsin Section; 2016 Mar 10; Wisconsin Dells, WI.

STUDENTS

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IMPACT OF WORK

This research reinforces the importance of understanding the interconnectivity between rivers and the shallow subsurface aquifer. We installed piezometers at five field sites along rivers of varying drainage size in southern Wisconsin and documented a significant reduction in the hydraulic gradient in the shallow subsurface aquifer in response to ice induced river stage peaks at all sites. This proves that the subsurface aquifer adjacent to rivers is much more dynamic system than previously thought during freezing conditions. Furthermore, as climate change continues to alter the environment, the immediate subsurface aquifer will also be indirectly affected due to differences in the length and frequency of ice cover caused by increasing wintertime temperatures.