SECTION 1. ADMINISTRATIVE INFORMATION

Title: An integrated assessment of lake and stream thermal habitat under climate change
Agency: U.S. Geological Survey
Principal Investigator: Jordan S. Read
Mailing Address: 8505 Research Way, Middleton, WI 53562
Telephone: (608) 821-3922 **Fax:** (608) 821-3817 **E-mail:** jread@usgs.gov
Total cost of project: $150,000
Period of time covered by this report: 2015-06-01 to 2016-09-30

SECTION 2. PUBLIC SUMMARY: Water temperatures are warming in lakes and streams, resulting in the loss of many native fish. Given clear passage, coldwater stream fishes can take refuge upstream when larger streams become too warm. Likewise, many Midwestern lakes "thermally stratify" resulting in warmer waters on top of deeper, cooler waters. Many of these lakes are connected to threatened streams. To date, assessments of the effects of climate change on fish have mostly ignored lakes, and focused instead on streams. Because surface waters represent a network of habitats, an integrated assessment of stream and lake temperatures under climate change is necessary for decision-making. This work will be used to inform the preservation of lake/stream linkages, prioritization restoration strategies, and stocking efforts for sport fish. This project employed state-of-the-science methods to model historical and future thermal habitat for over ten thousand lakes. These data were combined with observations of fish and stream temperature data to predict suitable fish thermal habitat. The results of this project have been used by partners and stakeholders to prioritize adaptation and restoration strategies for the region's freshwater resources. Additionally, these data products are shared openly in machine-readable formats in order to spur other innovation and research.

SECTION 3. PROJECT SUMMARY:

Lakes and streams are warming with negative impacts on aquatic ecosystems. Much is known about the warming of streams and rivers due to broad-scale modeling efforts and the existence of stream temperature monitoring networks. No such data existed for the state of the Nation's lakes, save for a few well-studied systems until this study. This project assembled a team of lake modelers, aquatic ecologists, fisheries biologists, and data scientists in order to fill this knowledge gap by reconstructing the modern temperature record in midwestern lakes (1979-2015). These data were then used to explain declines in important native fish and project future changes that will enable managers to prioritize resilient lakes.

As part of this project, we aggregated temperature observations and parameterized mechanistic models for over 10,000 lakes in the U.S. states of Minnesota, Wisconsin, and Michigan to examine broad-scale lake warming trends and among-lake diversity. Daily lake temperature profiles and ice-cover dynamics were simulated using the General Lake Model for the contemporary period (1979-2015) using drivers from the North American Land Data Assimilation System (NLDAS-2) and for contemporary and future periods (1980-2100) using downscaled data from six global circulation models driven by the Representative Climate Pathway 8.5 scenario, a "worst case" emissions scenario with utility for natural resource planning under extreme warming. For the contemporary period, modeled vs observed summer mean surface temperatures had a root mean squared error of 0.98°C with modeled warming trends similar to observed trends. Modeling scenarios and analysis of field data suggest that the lake-specific properties of size, water clarity, and depth are strong controls on the sensitivity of lakes to climate change. For example, a simulated 1% annual decline in water clarity was sufficient to override the effects of climate warming on whole lake water temperatures in some - but not all - study lakes.

Additionally, observational data was used to evaluate seasonality in warming trends and differences between lakes and stream warming rates. We found that lakes in northern Wisconsin were warming faster in the month of September that any other time of the year, and that the variability across streams in warming rates exceeded the variability across lakes. This is an important finding, because it suggests that there is more heterogeneity in the responses of streams to climate warming, perhaps due to other environmental filters including the impacts of changing hydrology and land-use.

SECTION 4. REPORT BODY

Purpose and Objectives:

Inland waters are experiencing widespread warming. The impacts on aquatic ecosystems are significant and accelerating. This is a problem for fisheries management, which is seeing range shifts and extirpations of valuable native fishes. With the aid of a national stream gaging network and the collaboration of motivated lotic researchers, much is known of temperature changes in rivers and streams. Temperature influences the distribution, growth, and reproduction of fish. Existing NE CSC and UMGL LCC projects have created regional databases of historical and predicted stream water temperatures. A complementary assemblage of lake temperature data, unfortunately, does not exist. As such, our project has generated lake temperature data in order to support the integrated study of lake and stream habitats for fisheries management.

Organization and Approach:

We organized this project to be steered by the needs of our state agency partners, and held various meetings to keep our efforts aligned with their needs. These partners represented state agencies of MN, WI, and MI Department of Natural Resources (DNR) agencies and several universities. Our project team had strong agency support, and we held monthly calls with the various teams. We also shared our results and initial plans with state DNR stakeholders at various stages of the project. As such, we modified parts of our project to respond to these new priorities. Stakeholder input led to changes including providing data releases and a web data visualization instead of our proposed data portal. We also modified our climate projection data to provide more up to date (and useful) predictions of future thermal habitat. In addition, our data subcommittee also gathered stakeholder feedback which was used to determine which thermal metrics should be calculated and shared in our tri-state data release (in addition to raw model output).

Our modeling approach for generating lake temperature data was designed to be fully reproducible, meaning we captured each step of data aggregation, processing, and model runs in version controlled scripts that were written and shared as open-source tools. As such, this also makes it easier for our team to add new lakes or migrate the framework to other states.

We employed a mechanistic water temperature model to generate water temperature profiles for thousands of lakes. This type of modeling, while more data and computationally intensive than regression-based alternatives, has two major advantages: 1) process-based lake modeling (such as this) is grounded by thermodynamic processes and is more valid in future conditions that would exceed the limits of empirical relationships (i.e., regressions would be extrapolated outside of observed data in a much warmer climate), and 2) by generating daily water temperature profiles, we can create a suite of metrics to use for various purposes (including multiple species of interest). The project used this approach to generate hundreds of metrics for limnologists and fisheries biologists instead of just focusing on one or two metrics that were particularly relevant to our study focus.

Fisheries observations were combined with static (e.g., lake size) data and dynamic (e.g., lake temperature) data under a Random Forest machine learning approach in order to find the most important predictors of successful walleye recruitment and high bass abundances within lakes. Walleye is a culturally and economically valuable coolwater fish, and bass are a warm water fish that has experienced an expanded range during climate warming. The details of this modeling approach can be found in Hansen et al. 2016 (reference below).

In addition to creating traditional research outputs and sharing the tools generated by this project, we also designed an interactive website for the general public. This was a recommendation from our stakeholder meeting and can be found here: https://owi.usgs.gov/vizlab/climate-change-walleye-bass. This website was featured by numerous local, regional, and national news outlets, and has become a useful tool for communicating some of the complexities of fisheries patterns within our partner states. Additionally, this site was nominated for a USGS Shoemaker Award for web communication.

Project Results, Analysis and Findings

Lake models were used to reconstruct historical temperature conditions in temperate lakes: Our project team created an innovative modeling framework that allows researchers to simulate daily water temperature profiles for thousands of managed lakes. These models were parameterized using remote sensing data, agency databases, and national-scale datasets (including the National Land Cover Database; NLCD). Gridded weather data was used to drive the models for over 10,000 lakes and the outputs were evaluated against temperature observations to determine model quality in various lakes. This effort involves the first ever mechanistic modeling project to operate at this scale, and was successful at creating useful data products for fisheries managers and researchers. With the help of another NE CSC PI (Michael Notaro), we simulated RCP 8.5 projected temperatures for lakes using six GCMs. Dr. Notaro provided downscaled climate data which were used to drive lake and stream temperature models. Our team shared results from both models with the Notaro project to be used in understanding range shifts for invasive species.

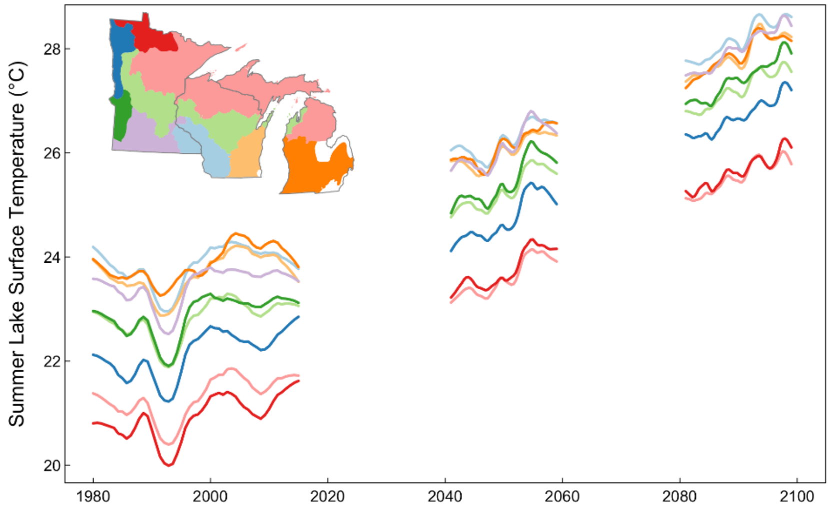

Figure 1: Ecoregions that included lakes modeled by this study, and their associated predicted summer temperatures (color-matched to map inset).

Most lakes in MN, WI, and MI have warmed substantially (1980-2015):

By evaluating lake temperature trends during 1980-2015, our group has concluded that most lakes in our study region (Minnesota, Wisconsin, and Michigan) have experienced surface water warming and decreases to ice-cover duration. These results are consistent with a recent global synthesis that found widespread warming in the summer surface water temperatures of hundreds of the world's lakes (onlinelibrary.wiley.com/doi/10.1002/2015GL066235/full). Our simulations agree with the observed temperature trends in the region, but also highlight regional differences in warming rates, such as enhanced warming near the Great Lakes (see Figure 2, JAS is July-September average surface water temperatures).

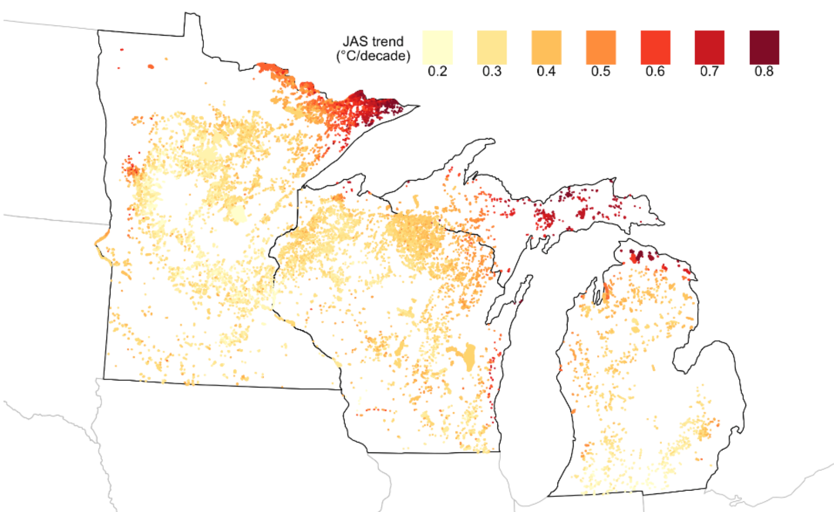

Figure 2: Lakes with daily temperatures modeled as part of this project. Lakes are colored according to summer surface warming trend. All lakes greater than 4 hectares with available depth data in the states of MN, WI, or MI were modeled.

Lake-specific characteristics can modulate response to warming:

Our research team found that water clarity, lake size, and lake depth can modulate the response of individual lakes to climate warming. Specifically, we found that clearer lakes are potentially more sensitive to climate variability and climate warming. Also, changes in water clarity can (depending on the direction of change) amplify or suppress the impacts of climate warming on lake temperatures.

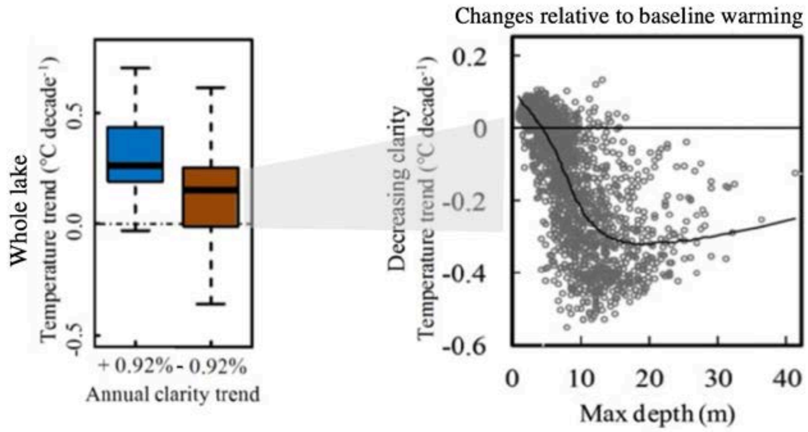

Figure 3: Adapted from Rose et al. 2016. The impact of increasing or decreasing water clarity on water temperatures was evaluated. For some lakes, a ~1% per year decrease in water clarity was enough to offset climate-induced warming of whole-lake water temperatures.

The warming of lakes Seasonal warming:

Climate warming may not affect water temperatures equally across seasons and depths. We analyzed a long-term dataset (1981-2015) of bi-weekly water temperature data in six temperate lakes in Wisconsin, USA to understand (1) variability in monthly rates of surface and deep water warming (2) how those rates compared to summertime average trends and (3) if monthly heterogeneity in water temperature trends can be predicted by heterogeneity in air temperature trends. Data for this portion of the study were collected by the North Temperate Lakes Long Term Ecological Research Program). Monthly surface water temperature warming rates were heterogeneous across the open-water season, ranging from 0.013 °C yr^{-1} in August to 0.081 °C yr^{-1} in September. Trends in monthly surface water temperatures were well correlated with air temperature trends, suggesting monthly air temperature trends, for which data exist at broad scales, may be a good proxy for seasonal patterns in surface water temperature trends.

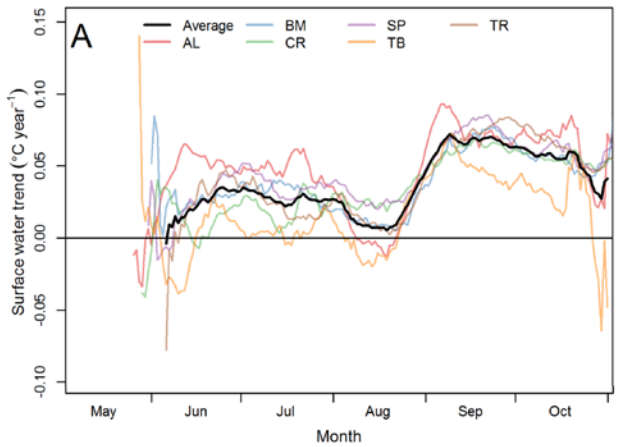

Figure 4: Adapted from Winslow et al. 2017. The seasonal warming rates of six temperate lakes were compared (varying colors), and we found stronger warming rates in the fall compared to mid-summer.

Differences in lake thermal habitat can explain differences in fish community dominance:
Recent declining walleye and increasing largemouth bass populations have raised questions regarding the future trajectories and management actions for these species. We developed a thermodynamic model of water temperatures driven by downscaled climate data and lake-specific characteristics to estimate daily water temperature profiles for 2,148 lakes in Wisconsin, US. Walleye recruitment success was negatively related and large- mouth bass abundance was positively related to water temperature degree days (see Hansen et al. 2017 for calculation details). Both species exhibited a threshold response at the same degree day value, albeit in opposite directions.

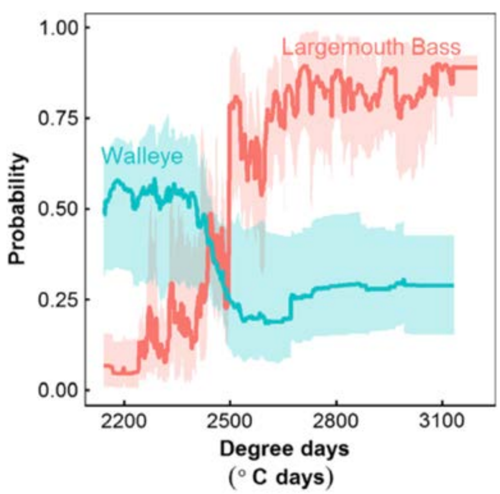

Figure 5: From Hansen et al. 2017. We found a temperature threshold (as water growing degree days) for walleye and bass in the state of Wisconsin. Walleye have experienced a state-wide decline over the past two decades.

Impact of lake warming on walleye recruitment varies by food-web contexts:
Water temperature is an important driver of spatial patterns in the relative abundance of walleye (Hansen et al 2017); we were also interested in understanding drivers of annual

temporal variation in walleye recruitment success. Using the knowledge and data established by Hansen et al. 2017, we analyzed predictors of annual walleye recruitment success as a function of annual, lake-specific degree days from 1989-2015. The relationship between water temperature and walleye recruitment varied among lakes, and was most negative in lakes with high largemouth bass densities. That is, warming negatively affected walleye recruitment in the contemporary period in lakes where largemouth bass were abundant, while warming increased the probability of recruitment in certain lakes where largemouth bass were not abundant. This work demonstrated that the effects of contemporary climate change depend on lake-specific food web contexts.

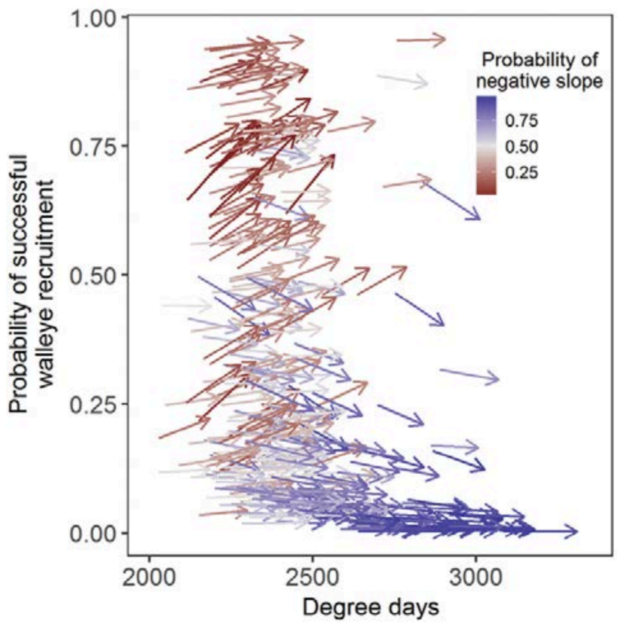

Figure 6: From Hansen et al. 2017. Each arrow represents an individual lake (N=359), its change in water temperature degree days from the 1980s to the 2010s, and the predicted effect of that degree day change on the probability of walleye recruitment success. Walleye recruitment probability increased in certain lakes with increasing degree days (red arrows), and decreased in others (blue arrows), although all lakes warmed in the contemporary time period.

We expect lake fish communities to continue to change:

Degree days (the best dynamic predictor of both walleye recruitment and bass abundance; Figure 6) were predicted to increase in the future, although the magnitude of increase varied among lakes, time periods, and global circulation models (GCMs). Under future conditions, we predicted a loss of walleye recruitment in 33–75% of lakes where recruitment is currently supported and a 27–60% increase in the number of lakes suitable for high largemouth bass abundance (reported range based on variability among GCMs). The percentage of lakes capable of supporting abundant largemouth bass but failed walleye recruitment was predicted to increase from 58% in contemporary conditions to 86% by mid-century and to 91% of lakes by late century, based on median projections across GCMs. Conversely, the percentage of lakes with successful walleye recruitment and low largemouth bass abundance was predicted to decline from 9% of lakes in contemporary conditions to only 1% of lakes in both future periods. Importantly, we identify up to 85 (of 2,148 WI lakes studied) resilient lakes predicted to continue to support natural walleye recruitment.

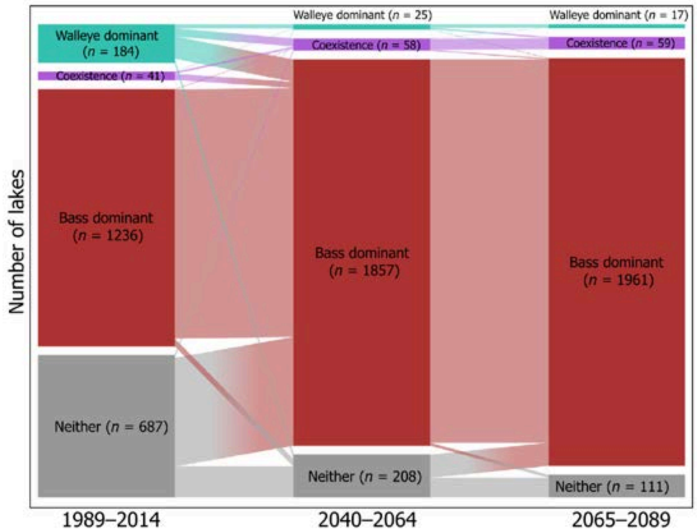

Figure 7: From Hansen et al. 2017. We projected changes to fish communities using modeled water temperatures in future time periods. While many lakes are expected to lose Walleye, a small number of lakes are predicted to retain Walleye even under extreme warming conditions.

Rates of warming are much more variable among streams than among lakes:
We examined modeled and observed water temperatures in lakes and streams and found that variability in warming rate is much greater in streams than in lakes. This is an important finding, because it suggests that there is more heterogeneity in the responses of streams to climate warming, perhaps due to other environmental filters including the impacts of changing hydrology and land-use. This finding is backed by the difference in spatial synchrony between important drivers of stream and lake temperatures. While lake temperatures are highly correlated with air temperature and cloud cover, streams are comparatively more sensitive to precipitation, which has a smaller (more local) synchrony scale. While there exists a large number of projects examining the impacts of stream warming, this is the first project to support an integrated assessment of warming in both lakes and streams.

Conclusions and Recommendations

Challenges for the project team:
This project was an ambitious effort and was challenging to fit into a shortened timeline. We planned for a two-year project, but due to the start of funding being later than expected, we began in earnest just before the last quarter of FY15. Our research team was also disrupted by several changes to the WI-DNR that modified the positions of two of our key collaborators. As such, we modified the scope of the project after discussing these challenges with NE CSC.

We also found it difficult to align our modeling outputs with the most recent and comparable climate scenarios and downscaled data products; we wanted the data generated by this project to have maximum utility, and modified the scenarios and GCMs used to simulate future conditions midway through the project. In order to also have comparable data for stream temperatures (part of being able to understand climate-induced changes in lake and stream habitat), we collaborated with a previous NE CSC researcher to re-run stream temperature models with the same modern scenario (and GCM) driver data. These simulations were not completed until December of 2016, delaying our ability to compare lakes to streams and also to finalize our lake/stream coupled model assessment of walleye habitat (walleye can find suitable habitat in both lakes and rivers). This effort is still ongoing at the time of this report.

Despite these challenges, we were continually encouraged by the project team's feedback on the progress modeling lakes in the Midwest. New ideas and uses of the data were often communicated to us from those at the DNR, and we have shared the datasets widely since their release.

Recommendations for next steps:

We focused on building temperature datasets that would be useful for explaining spatial and temporal patterns in fisheries data, including helping understand walleye declines in the Midwest. As we work to build on these results, we have received feedback from fisheries researchers and managers that maximizing the quality of individual lake models on particularly well-studied lakes would help fill some information gaps for state agencies. We call the ability to produce high-quality simulations at the local, state, and regional scales "hyperscaling" and are excited to pursue an extension to our project that included this work. As part of this project, we have assembled over one million water temperature observations (from over fifty different monitoring groups) and used them to validate our models across diverse lakes. Hyperscale modeling would extract more from these observations, using data assimilation techniques to integrate the observations into improving individual models at the local scale. These techniques have been used elsewhere to improve local-scale simulations (e.g., weather predictions), but have not been used in simulating lake thermal habitat.

The partner states for this project (Minnesota, Wisconsin, and Michigan) are three of the most lake-rich states in the Nation. Other states within the NE CSC footprint also place high value on their lakes and on the fishery economy. As such, the modeling framework created for this project would be useful elsewhere, including the entire NE CSC domain (which we noted as a future expansion option in our original proposal).

We have received extremely positive feedback when presenting on this project to stakeholders and also at national science meetings. The work we have accomplished within this two-year project has filled some knowledge gaps, but also exposed many other to important ideas that need further exploration. We were pleased to see the Midwest Association of Fish and Wildlife Agencies Climate Change Technical Working Committee Report 2016 highlight "Impact of climate change on lake systems and fish habitat" as the first of four regional climate change research priorities. We consider the research and dataset production that this project has led to be in direct service of this priority. As a result of collaborations that were formed during our stakeholder meeting, we have also provided data to Aaron Shultz, a Great Lakes Indian Fish & Wildlife Commission Climate Change Fisheries Biologist, who is using the data to explore potential drivers of change to bass populations. Our project partners at MN-DNR, WI-DNR, and MI-DNR in addition to members of the Midwest Glacial Lakes Partnership continue to use these data as part of fisheries analyses; several analyses have resulted in publications led by state agency researchers already.

Continuing to evaluate the impact of climate change on lake and stream fish using coupled and comparable modeling approaches should be a priority. We have not yet completed the portion of this project that evaluates the potential for climate refugia provided by connected lakes and streams, but early analyses and common sense suggests we should include lakes and streams in assessments of climate change impacts on aquatic ecosystems.

Outreach and Products

Peer-reviewed articles resulting from this funding:

1. Winslow LA, Read JS, Hansen GJA, Rose KC, Robertson DM. 2017. Seasonality of change: Summer warming rates do not fully represent effects of climate change on lake temperatures. *Limnology and Oceanography*, (5), pp.2168-2178
2. Hansen, G.J., Midway, S.R. and Wagner, T., 2017. Walleye recruitment success is less resilient to warming water temperatures in lakes with abundant largemouth bass populations. *Canadian Journal of Fisheries and Aquatic Sciences*, (999), pp.1-10.
3. Winslow LA, Hansen GJ, Read JS, Notaro M. Large-scale modeled contemporary and future water temperature estimates for 10774 Midwestern US Lakes. *Nature: Scientific Data*. 2017, (4).
4. Winslow LA, Chamberlain S, Appling AP, Read JS. 2016. sbtools: A package connecting R to cloud-based data for collaborative online research. *The R Journal,* (1), pp.387-98.
5. Read JS, Walker JI, Appling AP, Blodgett DL, Read EK, Winslow LA. 2016. geoknife: reproducible web-processing of large gridded datasets. *Ecography*, (4), pp.354-60.
6. Rose KC, Winslow LA, Read JS, Hansen GJ. Climate-induced warming of lakes can be either amplified or suppressed by trends in water clarity. 2016. *Limnology and Oceanography Letters*, 1(1): 44-53.
7. Hansen GJ, Read JS, Hansen JF, Winslow LA. Projected shifts in fish species dominance in Wisconsin lakes under climate change. 2017. *Global change biology*, (4), pp.1463-76.

Conference presentations, seminars, webinars, workshops given by research team members:

1. Gretchen Hansen and Jordan Read. Climate change effects on Wisconsin lake temperatures and fish populations. Presentation at the UW-Madison's Center for Limnology graduate symposium, October 2015.
2. Luke Winslow and others. Modeling past and future thermal conditions for 2,500 Wisconsin managed lakes. American Fisheries Society 145th Annual meeting. August 2015.
3. Gretchen Hansen and others. Resilience of Walleye thermal habitat to climate change in Wisconsin lakes. American Fisheries Society 145th Annual meeting. August 2015.
4. Gretchen Hansen and others. What’s the deal with Wisconsin’s walleye? (Webinar). Climate Change Science & Management Webinar Series (NCCWSC). September 2015.
5. Luke Winslow. Some like it hot: Understanding past and future climate trends and impacts in Mid-western lakes. National Wildlife Health Center. April 2015
6. Luke Winslow and others. Seasonally non-uniform responses to climate change in temperate lakes. ASLO Ocean Sciences meeting. February 2016.

7. Jordan Read and others. Modeling the past and future of 10,000 economically valuable lakes: Applying water and climate data to management needs. presented to the Join Research Committee and Federal Geographic Data Committee. March 2016.
8. Jordan Read and others. Mechanistic Lake Modeling to Understand and Predict Heterogeneous Responses to Climate Warming. American Geophysical Union Fall meeting. December 2016.
9. Gretchen Hansen. Understanding and predicting change in inland fish communities. University of Minnesota Conservation Science Seminar Series, St. Paul, MN. November 2016.
10. Gretchen Hansen and others. Using species-environment relationships to guide fisheries management in a changing climate. University of Minnesota Conservation Science Fisheries and Aquatic Biology Seminar Series, St. Paul, MN. January 2016.
11. Jordan Read and others. Understanding and Predicting Heterogeneous Thermal Responses of Inland Waters to Climate Warming. American Fisheries Society 146th Annual meeting. August 2016.
12. Luke Winslow, Jordan Read and others. GLM-AED Lake Modeling workshop. University of Wisconsin-Madison and USGS modeling training course, Madison, Wisconsin March 2015.
13. Jordan Read, Luke Winslow and others. Tools for access, manipulation, and modeling of federal water and climate data. Office of Water Information USGS workshop. Webex, and in person Middleton, Wisconsin March 2016.
14. Jordan Read, Luke Winslow and others. Towards Integrated surface water modeling National Flood Interoperability Experiment Workshop, Chapel Hill, North Carolina January 2015.
15. Jordan Read and others. A new era of freshwater science. National Science Foundation. May 2016.

Communications with decision-makers:

1. A stakeholder workshop was hosted by the team in Feb 28-Mar 2 2016. The workshop was attended by USGS, MI-DNR, MN-DNR, WI-DNR, UW-Madison, University of MN, Michigan State University, and Great Lakes Indian Fish & Wildlife Commission.
2. Luke Winslow and Jordan Read presented to the Midwest Glacial Lakes Partnership in May 2016.
3. Gretchen Hansen and Jordan Read hosted a webex to show the pre-release version of https://owi.usgs.gov/vizlab/climate-change-walleye-bass/ to WI-DNR fisheries managers for feedback in July 2016.
4. Jordan Read presented to the Midwest Glacial Lakes Partnership in November 2016.
5. Luke Winslow, Gretchen Hansen, and Jordan Read held a meeting at the WI-DNR to gather feedback on design of this project in May 2015.

Websites created for the project:

1. https://owi.usgs.gov/vizlab/climate-change-walleye-bass/

Data releases and tools:

1. Winslow LA, Rose KC, Read JS, and Hansen GJA. 2016. Climate warming of lakes can be either amplified or suppressed by trends in water clarity: U.S. Geological Survey data release, http://dx.doi.org/10.5066/F7028PN4.
2. Hansen GJA, Read JS, Hansen JF, Winslow LA. 2016. Projected shifts in fish species dominance in Wisconsin lakes under climate change: U.S. Geological Survey data release, http://dx.doi.org/10.5066/F7X0655K.
3. Winslow LA, Hansen GJA, and Read JS. 2016. Data release: A large-scale database of modeled contemporary and future water temperature data for 10,774 Michigan, Minnesota and Wisconsin Lakes. U.S. Geological Survey data release. https://www.sciencebase.gov/catalog/item/57c5c793e4b0f2f0cebdaa4d
4. Read JS and others. Processes gridded datasets found on the U.S. Geological Survey Geo Data Portal web application or elsewhere. https://CRAN.R-project.org/package=geoknife
5. Winslow and others. Tools for interacting with U.S. Geological Survey ScienceBase interfaces. https://CRAN.R-project.org/package=sbtools