Variable Warming in Lakes of the Upper Midwest and Implications for Sport Fish

John Ossanna: [0:05] Welcome from the US Fish and Wildlife Service's National Conservation Training Center in Shepherdstown, West Virginia.

[0:10] My name is John Ossanna, and I'd like to welcome you for our webinar series held in partnership with the US Geological Survey's National Climate Adaptation Science Centers.

[0:20] Today's webinar is titled "Variable Warming in Lakes of the Upper Midwest and Implications for Sport Fish." We're excited to have Jordan Read from the USGS with us today. To introduce our presenter, we have Aparna Bamzai-Dodson, I hope I said that correctly, who is the deputy director of the North Central Climate Adaptation Science Center. Aparna?

Aparna Bamzai-Dodson: [0:41] You said that perfectly. Thank you, John. Jordan Read is a USGS data scientist with a background in physical limnology and modeling. Jordan works with others to develop frameworks for reproducible research and data visualization and new methods to combine traditional process-based models with machine learning.

[1:02] Jordan approaches research questions that involve lake and stream simulations with sensored data analysis, including the challenges of modeling over tens of thousands of lakes across the US.

[1:12] As part of collaborating with regional and local scientists interested in climate impacts on lakes, Jordan is a principal investigator for the Long-Term Ecological Research North Temperate Lakes site, a lead PI on a project to model climate change impacts on lake temperatures, and has served as a steering committee member of the Global Lake Ecological Observatory Network.

[1:33] Jordan is an associate editor of the journal "Limnology and Oceanography Letters" and the chief of the Data Science Branch within the USGS Water Mission. Thank you so much for being here today, Jordan.

Jordan Read: [1:44] Thank you. I'm going to pop up my slides, hope this goes off without a hitch. I should be sharing. Can you all see my screen? If somebody can give me an affirmative?

[1:58] [crosstalk]

Jordan: [1:58] Great. Thank you for the invitation and the introduction, Aparna. I'm really gracious for this opportunity to speak to this audience on this topic that I'm really passionate about, which is lake responses to climate change.

[2:16] I want to thank, specifically, my co-PI Gretchen Hansen who's at University of Minnesota, Twin Cities, and our many other collaborators, many of which I'll give a shout-out to throughout this talk that have been working on this and related projects for years in this topic.

[2:38] To reinforce that I'm speaking on behalf of a lot of partners, and we've had a lot of excellent support from the National Climate Adaptation Science Center, and both the Northeast and the North Central Climate Adaptation Science Centers to get this work initiated and to move it along, in addition to our other funders, which I'll recognize at the tail end.

[3:01] This talk will focus on lakes in the Midwest. To set the stage here for this talk, when you look at an overview of the Midwest, lake features are something that really pops out. They're key elements in the landscape of the Midwest. It's not just the Great Lakes. These lakes are numerous and they're prevalent.

[3:25] Likewise, these lakes are important for economy, recreation, cultural, and ecosystems. We really need to understand these lakes to make informed decisions that are related to either sustaining, adapting, or enhancing our relationships and expectations about lakes.

[3:46] Meanwhile, we're, of course, experiencing a lot of change in lakes. I would argue that lakes are one of the areas where we see one of the strongest expressions of climate change. Several years ago, we published a study that assembled temperature data that was both collected in situ, meaning many of our partners went out and sampled these lakes over decades.

[4:12] We also put together remote sensing satellite records and put together this synthesis of trends showing that 90 percent of the lakes that were in this global study, which included the largest lakes on Earth, were warming. There was a significant amount of variability in warming across lakes as well.

[4:40] To go back to the Midwest, we're seeing a lot of change in fish populations in these lakes. If we take a look at the regional or state level at fisheries data that can be aggregated together, we see a number of patterns that emerge, either increases or decreases.

[4:59] To point out a couple of them, we see in Wisconsin declines in really valuable cool-water fish such as walleye. We see increases in some warm-water fish. On the lower left-hand corner, you see an increasing trend in largemouth bass across the state of Minnesota.

[5:22] Just like what I mentioned about warming trends in lakes, if you get down to the lake-specific level, you see a lot of variability in these trends.

[5:32] In aggregate, the previous slide, we see trends up and down in key fish. If we look at individual lakes, we got variability in these trends. We need to understand specifics about these lakes that result in this variability in order to understand and manage expectations for the future.

[5:57] These aren't just academic exercises, where we want to hatch a question, and maybe nobody is interested. This is critical information that the public is really keyed in on, so just a few highlights from some Midwest publications that highlight changes and expectations for fisheries openings and declines.

[6:29] We're just showing the headlines here. If you get down into the comments section, you'll see a lot of energy and a lot of excitement about [laughs] either management decisions about these declines or about the experiences and the differences compared to one's childhood.

[6:49] In order to address this particular problem, so understand changing climate and the impact on sport fish, we've established the suite of projects that are centered around this Midwest Glacial Lakes Partnership, which is a fishing and wildlife regional fish habitat partnership.

[7:11] It forms the collaborative backing of this group. I'm showing here the spatial extent of that Midwest Glacial Lakes Partnership. Within this project, we have two main goals that I'll talk about today. One of them is to leverage this cross-state data expertise and environmental gradients, so that we can better understand climate change impacts on Midwest sport fish.

[7:39] Then the second one seems to be a goal that goes hand in hand with doing any broad-scale work, which is the need to dig in and look specifically at, often, lake-by-lake management questions. We want to augment regional predictions with local observations and knowledge to address critical lake management questions.

[8:05] For the remainder of the talk, I'm going to be focusing the first half on project goal number one. Then, the second half, I'll dig back into lake-specific tools and questions.

[8:17] For the first one, taking advantage of this spatial extent and the expertise that's shared across the academic groups, the federal partners, the state agencies, in sharing data and sharing knowledge in order to give us the appropriate models and data to answer these important questions.

[8:40] I want to acknowledge this is a subset of the Midwest Glacial Lakes Partnership, and the science and data team in-person meeting that was back in Minnesota.

[8:50] I don't think this represents the entirety of that team, but getting together and providing some guidance and some backing for this project. I just wanted to give them a shout-out and recognize how critical they've been to establishing the direction of this particular project.

[9:12] Understanding warming and fish responses to climate change is often approached using empirical models that use often air temperature as a proxy for water temperature, since we have air temperature observations in many locations.

[9:35] The air temperature change that we get off of our climate projections is often front and center for managing expectations for the future. Many of us would build models that tell us something about temperature change, or about water temperature change, based on air temperature change.

[9:54] You can see here is northern Wisconsin air temperature versus water temperature. There is a pretty strong relationship there, and with some other predictors, you can expect to back out a good bit of that variability, but when we're looking at climate change, and specifically looking at conditions, that in some cases, they are going to be warmer than we have yet to observe locally.

[10:20] We want to be a bit wary about the transferability of these relationships, both in space and into the future, so in time. Here, if we compare this to...this is just an example in Kansas to highlight what happens when we get warmer and warmer.

[10:41] Different lakes, in different regions, will have a different degree of flattening out at the top here, revealing that there are some other important factors, other than just air-temperature warming rates, that we'll need to take into account.

[11:00] Instead, our project has focused primarily on using a process-based understanding of the controls of lake temperature, so that we can get down to the root of what makes temperature change from a day-to-day and a week-to-week and a decade-to-decade sense. If we understand trends in those individual components, we can have better expectation for the future.

[11:28] What do we need to do to build that process-based understanding of lake temperature change? We need to know some things about the local climate of these individual lakes.

[11:41] Likewise, we need to know something about the size and the depth of the lake. If a lake is very large and shallow, it's probably going to be fairly well-mixed, meaning it won't have much of a temperature difference from the top to the bottom versus a small, sheltered, protected lake might have a very warm surface-water temperature, but then still plenty of good, cool-water habitat in the bottom.

[12:10] Those are important things for us to be able to include in our modeling approach. Then, like I mentioned a little bit before, the degree which these lakes are sheltered from the wind, so understanding local canopy cover and its impact on reducing these wind-driven fluxes, like the rate at which the lake evaporates, and the mixing energy and whatnot.

[12:42] Then lastly, these high-level controls on lake temperature, the water clarity matters for the aesthetics of the lake, and also for safe predation. It also, of course, has this impact on the vertical, thermal structure of lakes. A clearer lake has deeper penetration of solar energy, so more sunlight gets towards the bottom of the lake.

[13:15] Darker lakes are warmer closer to the surface, because they have more of that energy attenuated close to the surface. What this means is, all other things equal, that darker lake might be a bit colder in the bottom compared to the clearer lakes. We need to take all of these things into account.

[13:35] By doing so, we can build these process-based, or some folks call them mechanistic, models that allow us to fairly resolve time step.

[13:48] In this case, we're showing daily simulations, daily time step, to build a vertically resolved record of water temperature with the model, with a caveat. If we have good information for all of those, we can do a good job, with a model like this, in reconstructing historical observations.

[14:16] Here is an example from Northern Wisconsin for one summer season. We have a lake that has warmish temperatures, close to 30 degrees towards the surface, but then lots of cool water habitat towards the bottom. You can see the model's ability to reproduce that, in addition to it's ability to resolve these warming and cooling fronts that move through.

[14:47] If we were interested in this one lake, and if we had, say, fisheries observations on a monthly scale or sparser than that, we could potentially reconstruct this temperature record to complement that. We would understand how temperature is changing, and how that may explain some of the trends that we have in the fisheries data.

[15:16] The real power of this type of approach is using these nationally available data sets and also a lot of manual digging to scrape PDF files for information on the morphometry of lakes and dig up old temperature records and all kinds of things to eventually put together the data needed to model lakes at scale, so that we can field one of these daily water temperature models for all of the lakes of interest for management, including thousands or tens of thousands.

[15:52] Here, I'm showing just a local snippet, because it's overwhelming to look at an animation, like this, at bar scale. A local snapshot of surface water temperature is coming out of these simulations. You've seen this through, about once by now, and what probably sticks out to you is the relationship across these lakes where there is a lot of coherence. There is a lot of similar behavior as they march through the spring and into the summer.

[16:31] Then one thing to point out, as you watch this a second time, is you start to see a bit of this heterogeneity, so even though there's strong agreement on what's happening through these seasons, you see things like the smaller lakes flicker a little bit more. The larger lakes are a little bit slower to warm in the springtime.

[16:55] What we understand, from evaluating this data and their relationship with the biological data that we also collect alongside, is that these differences, although being somewhat visually small, right now, really do matter. We can take this modeled information and generate metrics that we consider to be relevant to our biota of interest, such as growing degree days.

[17:26] Here, we take the annual daily animation and we turn it into a single metric for a given year, so within a year, calculating the growing degree days for each individual lake.

[17:41] There, you start to see some of these differences, across lakes, that may not have been as visible on the daily scale. We can map these out. Of course, here, we're looking within one county. If we looked wider, we'd see a much wider spread of this particular metric, as well.

[18:07] What can we do with this metric? Gretchen Hansen's work that was published back in 2017, used our models just for the State of Wisconsin, but evaluated this in addition to many other water-temperature-derived metrics to attempt to predict the probability of successful improvement for walleye and the probability of largemouth bass relative abundance in this Wisconsin locus.

[18:45] With all of the temperature metrics that were fed into this model, most of those fell out as being either redundant or less important.

[18:56] This growing degree days popped out as being the key one. If you are interested in this warming relationship where, clearly, these cooler lakes are, all other things equal, doing better for walleye recruitment success, but then as we move into higher degree days, largemouth bass relative abundance is expected to be greater than walleye recruitment, kind of knocks off.

[19:27] This is really important context to have for some of these patterns that we've seen in the State of Wisconsin and in other Midwest states.

[19:35] Likewise, we can combine those with the other elements of the model, including the depth of the lake, some clarity information, and its size, and to be able to categorize individual lakes, as to whether or not they're more likely to be dominated by largemouth bass or walleye or potentially coexist.

[19:57] Gretchen's work did this for the contemporary period, with these available data, and found that for the State of Wisconsin, the majority of this study, lakes were bass-dominant. A smaller fraction, but which ended up being the larger of the lakes, was walleye-dominant, and then a small fraction of lakes co-existing.

[20:22] Then what we are able to do with climate projections is to look at transitions through time. As we move into a mid-century period, where we got warmer conditions and, of course, a response from the lake, which is also to warm up, we see an increase in the number of lakes that are bass-dominant.

[20:45] Some of those are because we're potentially losing walleye lakes to become bass-dominant. But, in other cases, we're creating new opportunities for bass, by taking some of this neither category and moving up into the bass-dominant. Then if we take that towards the end of the century, that pattern continues.

[21:10] Gretchen's work, in that study and in a later work, also looked at these lake-specific factors, such as the relationship that I showed, with temperature is very clear and compelling, but there is, of course, caveat for that.

[21:27] That relationship is a little bit different when you select it across lake size, so on the plot on the left, you've got lakes at about a hundred hectares having this huge falloff in walleye recruitment success as in higher degree days versus lakes that are larger or maybe a bit more resilient to that warming.

[21:53] Then in the plot on the right, just to note that warming increases recruitment success in some lakes, but it decreases it in others. The presence, in this case, of largemouth bass might influence that response, too, so there's multiple lake-specific factors that may provide a different signal and need to be interpreted.

[22:20] Hanging on that point about lake-specific knowledge, it's important to get this to the second part of the project goal. First, we were using these broad gradients, and there's probably available information or knowledge, to generate models and some expectations. Now, we're trying to do that very challenging thing, where we take regional work and we make it locally accurate and locally relevant.

[23:00] I'm going to go over two use cases, for how we've moved toward that, in this project. The first of these is to make better predictions by taking more advantage of data in these models. Then the second of these examples is to include other dynamic factors that need to be taken into account locally. For this one, we'll talk about thermal-optical habitat for walleye in Minnesota.

[23:41] The first of these, improve our local estimates or local knowledge of change, is to improve water-temperature models by taking advantage of local data. I glossed over the modeling results that focused mostly on outcomes and on surface-temperature metrics.

[24:12] The hidden truth here is that, despite putting a lot of energy and effort into this modeling approach, doing broad-scale models still has its flaws. At this scale, we have many cases where estimating deeper-water temperatures or even water temperatures in the middle parts of the lake, with respect to depth during the summer, is challenging and is fairly error-prone.

[24:41] Here is the plot. You'll see there's what is basically model residuals, so taking a model and then subtracting out what observations we have. We see that the model is up. In some cases, it's as much as five degrees.

[24:58] That's really not acceptable for use in these fisheries research questions, because it's just simply not good enough, which is why the work today is focused on the surface temperature estimates, which are reliably better.

[25:17] But because we're really interested in getting those answers for deep waters, at this relevant scale, for management to understand, we need to figure out if there are more possibilities available to us.

[25:35] We started working with Vipin Kumar out of University of Minnesota, Computer Science Department, who is really an amazing collaborator and the work that he's done to date is very relevant, because he's looking at data-driven approaches for understanding climate impact. We were able to start partnering with Vipin in an early stage in this to develop some new approaches for improving these models.

[26:07] We've refined the language that we used to talk about these, to zoom in on this concept called process-guided, deep-learning predictions. We've got a number of papers, in various stage of publication, including one that is currently in review, that I'm going to talk about for this use case, but it's been a really exciting research pairing with Vipin's group.

[26:35] The question we have, right off the bat, is we know that with some of these advanced machine learning modeling approaches, that we can beat these so-called process-based models, so that the modeling approach that I've been talking about here, for the most part, is process-based, meaning we constrain it with our physical knowledge of the system.

[26:58] But we can use a completely different approach, empirical approaches, like regression or some of these more advanced machine learning approaches that ignore these physical relationships and focus on the pattern in the data and how to reproduce that.

[27:21] When there is enough information, those types of data-driven models, hands down, can do a better job of reproducing the pattern than our process-based models. That's the right-hand side of this plot, with more temperature data in these models, a deep learning model is more accurate than a process-based model.

[27:45] But on the left side of this, if we have less and less data, in many cases, with this type of work, we have no observations or they're very sparse. That's when this type of model, a process-based model, really excels.

[28:04] Our work with Vipin's group really went after hybridizing these two approaches, so went after including these process components into deep learning models.

[28:17] What we're doing here is if you think back to the early part of this talk where I was mentioning all of the different climate drivers that need to be taken into account to understand the rate of evaporation in the lake, what incoming solar radiation, and along with radiation, we were able to encode those modeling components into an otherwise data-driven model that learns from our existing process-based model.

[28:47] The exciting part is that, as of course might be expected, it does better than both of the approaches in all of these conditions.

[28:57] What does this mean for our problem with model bias in the deep water? It's just one example here, but we can use these models to do a much better job at these types of predictions and thus, we'd be able to with more confidence, apply them to more thermal guilds of interest.

[29:23] Just to communicate where we are with this particular part of the projects, we've been working with Vipin's group for a year and a half now, developing and applying these methods and working on how to scale them up.

[29:40] Alison Appling, who is a USGS employee, has been working with their team, as well, to reconfigure their approach onto something that we can run on USGS infrastructure and has gotten us to the point where we are able to run hundreds of models using this approach with available data, hundreds or thousands, to where our computing is no longer the limiting resource here.

[30:13] Moving on from process-guided deep learning, improvements of water temperature and moving into very lake-specific applications of this type of work, improving temperature is great.

[30:27] Those estimates are really critical for being able to say much of anything about broad-scale environmental change when it comes to lake fisheries. In some cases, temperature alone is not going to give us what we need.

[30:42] In Mille Lacs, which is a critical lake in Minnesota, we've got the most historically popular wildlife fishery has been in decline while faced with several environmental and anthropogenic factors. Here's the time series of the decline, starting in the '90s and getting us close to present day.

[31:08] We've got a number of ecosystem changes that are happening at the same time. We have a clearing of the lake. The water clarity is becoming clearer. You may think, "Oh great, you know. Better water clarity. That must mean the lake is healthier or better."

[31:29] You may not feel that way if you're a walleye because you'd be a low-light specialist. You'd do better in lower light conditions as a predator. You do better in these low-transparency conditions.

[31:45] If you're a walleye, you're fairly bothered, potentially, at this zebra mussel invasion. At the same time, we have overlaid a period of warming. When examining this problem, we need to understand the interactions between these water clarity changes and water temperature changes and what that means for walleye.

[32:13] Luckily, we have some precedent here. In 2004, Lester et al wrote this paper on thermal optical habitats. The idea of if we can understand this intersection between the appropriate amount of optical habitat and the appropriate water temperature, that we can do a better job at predicting the success or sustainability of the walleye population.

[32:46] If we are able to take incoming information about the solar radiation, so the visible light coming from the sun, how much of that is available at various depths, we can create a relationship for the ideal optical habitat for walleye. We can look at how that varies through time because we have an understanding of how the water clarity changes through time.

[33:16] We also can take our existing water temperature models and create those yearly metrics for thermal habitat using optimal conditions for walleye as well. Note here that we've got trends in optical habitat with a decrease, thermal habitats more or less the same, maybe, a little bit of warming, and the thermal optical habitat itself has this decrease pattern.

[33:47] How do we apply this? How do we take this information and turn it into something that would be useful for managers to understand and communicate? We can use the framework, the safe operating space, and apply it to this fishery in Mille Lacs.

[34:08] Say, we've got a starting point where we've got a safe or sustainable space for this fishery, meaning if we keep operating in this area, we're not going to run into too much trouble with the future populations.

[34:26] Environmental change can push us outside of this safe operating space, even if we're not modifying the harvest of the amount of walleye that we're removing from the system. Usually, once we get out into this unsafe spot, we might expect a management response to hop in and reduce the walleye harvest available, to get us back down to that safe operating space.

[34:57] Alternatively, if we can understand and adapt to this change as it's happening, we can propose an alternative, more efficient pathway that keeps us operating within the safe space as we move through environmental change.

[35:14] Gretchen, who's been very productive with this work at the intersection of climate change and fish, recently has a paper accepted in "Ecosphere" that applies the safe operating space with Mille Lacs and thermal optical habitat for the walleye fishery.

[35:37] If you look at Figure 1, this curve denotes there's a non-linear relationship between habitat and safe harvest. When we compare it to a historical harvest, we can see that we've overharvested about half of the time, give or take.

[35:55] In more recent years, we've been well within the safe limits. Just as a note, recreational harvest has been closed for much of the past four years due to low biomass. Yes, we'd expect that that harvest in recent years would be within safe because it's been closed.

[36:13] If we shift over to how these data can help us understand these impacts for years out in Figure 2, in most cases when harvest has exceeded what we've estimated as a safe harvest based on this thermal optical habitat, the population has declined the following year.

[36:37] A pretty compelling example of how the combination of temperature change, optical habitat change, and also having appropriate information on the harvest pressures can allow us to understand this change through time.

[37:02] We can use this information, not just in Mille Lacs, but at broader scales to both manage our lakes and also manage expectations if we can make these connections with the data to the public.

[37:16] I want to hop to just an overview of where we consider this project to be and what we're hoping to do next. I hope this has been a decent overview that gives you the flavors of this project. It's been a great collaboration that's included a bunch of dimensions that I hope I've done justice to within the time limits here.

[37:50] I know there's, of course, plenty more to talk about and more questions that are likely to come up. What we're working on right now is finalizing and releasing these model runs at this expanded geographic scope.

[38:06] This includes the Dakotas, includes some work in Iowa and releasing those as one, big data release package at this scale, at the Midwest Glacial Lakes Partnership scale for external and internal, and all kinds of different uses.

[38:30] The next thing we hope to do is to be able to go as far as we've shown in specific states. The examples I've had have been state-specific, Minnesota and Wisconsin. We want to dig into more cross-site, biological synthesis work.

[38:52] The hard part of meshing up fisheries data across states and using that to build multi-state fisheries models that take advantage of these big environmental gradients so that we can get a better understanding and expectation for change.

[39:11] Then lastly, I didn't spend much time on this today, but we've been focusing on making sure that any important scientific output that we've got that's in a traditional publication also is able to find its way into a public-friendly product that we can use for communication and expectation management.

[39:36] We're pointing out a previous data visualization we did on the work that was specific to Wisconsin. We hope to continue doing similar work to connect stakeholders with the appropriate tools and data that they need.

[39:55] Lastly, I wanted to thank the funders and partners that have made this work possible and hope that there's a little bit of time for questions.

John: [40:06] Thank you.

[40:39] I want to thank everyone who participated in the event. I wanted to thank USGS, their help, and Elda, and all that with continuing this webinar series.

there we go. "Use the concept of growing degree days. Is that an air temperature-based metric, or is it adapted for aquatic application?"

Jordan: [41:29] Good question. If you're familiar with growing degree days, it's the cumulative sum of degrees above a certain threshold through a year or season. It's common for ag. Usually, that would be air temperature degree days, but here we're using water temperature growing degree days.

[41:53] It is the lake temperature version of that calculated in the same way that we'd calculate an air temperature-based growing degree day.

John: [42:04] Thank you, Jordan. "What kind of fish are in the neither lakes?" The lakes that aren't dominated by walleye or the bass.

Jordan: [42:14] A question about the map we've got here. The lakes that would be in black. I'm going to let Gretchen answer that.

Gretchen Hansen: [42:26] What fishes are in the neither lakes? That means that can we classify bass lakes as did they have a high abundance of largemouth bass? It's likely that those lakes still have some largemouth bass in them because almost every lake in Wisconsin does. They don't have natural water recruitment.

[42:46] They may also have walleye in them if the walleye are stocked, just not natural recruiting. Then there are a number of other species as well that might be there that we didn't model in this study.

John: [42:59] Thank you. Leslie says, "One of these publications out now further address your point, process-guided, deep learning, model performance superior for out-of-bounds data sparse and data rich conditions."

Jordan: [43:19] The only paper that tests all of those is the one that is in review right now that I was showing results from...I'll just get back to...These results are all from that paper. This is the point where this question is coming from.

[43:43] Superior for out-of-bounds data-sparse and data-rich conditions. We're in review with that. Hopefully, we'll have something to share in the next, say, five months or so for that being a publicly available publication.

[44:02] If you are interested in any of those details, feel free to email me, and I can share examples with you. Just to elaborate on those experiments, we tested out-of-bounds predictions.

[44:16] One of the challenges that you have with a data-driven approach or one of the common critiques is that if you train or build a model with colder climate, then you attempt to predict warmer climate, it's probably not going to do a very great job because the test data, the data that you're interested, are out of bounds of it.

[44:42] We evaluated that, both based on training only with the colder years on the record. Then, also, only with training a model with springtime and fall temperatures, and then attempting to predict the warmer summer period.

[44:59] In all of those situations, the model performance based on a [inaudible] air temperature was better for this process-guided deep learning versus a powerful but purely data-driven approach of a deep learning model that is time aware and also versus a calibrated process-based model.

[45:24] Those process-based models, they're the ones that I was focusing on for about the middle quarter of the talk or so. I hope that answers the question.

[45:36] I know that's not satisfying. I don't have a paper link that I can send you to right now. The papers that we do have on this topic or the main findings are that the modeling approach is more accurate in data-rich and data-medium conditions, but those papers do not test the out-of-bounds predictions.

John: [45:59] Thank you. We've got another question from Ryan. "They must have seemed fairly extensible to larger geographies. What are the limits to this approach, assuming there is enough data?"

Jordan: [46:11] Great question. [laughs] I would say the limits to this type of modeling approach -- this is just a big issue for lake studies in general -- is absence of information on lake depth. That is the hardest bit of information for us to dig up.

[46:35] As I mentioned earlier, pulling data from PDFs, from old bathymetric or maps from lakes from the '60s or so is one of the ways that we attempt to get all of that data together. That's something that gets in the way of doing modeling like this at, say, the national scale is you do need to make some assumptions about lake depth.

[47:05] Unfortunately, attempts to predict lake depth from other landscape characteristics aren't very accurate on a lake-specific basis. They can do a decent job at broad skills, but what we need to have is an accurate idea of how deep the lake is to do a good job with it.

John: [47:27] We have a question from David. "For those lakes where walleye are no longer projected to be supported, has there been explicit consideration of stocking those systems with a more thermal suitable species?"

Gretchen: [47:41] Yeah. First, I would say there are more thermally suitable species that probably don't need to be stocked in those lakes, for example, bass or bluegill. Other warm water species are probably in most of those places there and doing just fine. There's no need for stocking.

[48:04] Of course, angler preferences play a role in what gets stocked. There's some ongoing work that Ralph Tingley is doing with Craig Paukert at Missouri to extend this working with [inaudible] to look at because we were looking at walleye recruitment in this case. Just saying, can the walleye naturally reproduce in this lake?

[48:27] Ralph is extending that work by also looking at adult life stages, which I think will be more relevant for stocking decisions. We find that adult walleye have a different thermal response curve than walleye recruitment does.

[48:42] We find a number of lakes where, maybe, they no longer are predicted for recruitment, but adults would still do OK. Those might be a good place to think about stocking versus places where recruitment is still going on. No need to stock there, or places where neither life stages are coordinated.

[49:01] Maybe, it's time to start thinking about a more thermally suitable species and focusing management on that. Hopefully, that answers the question.

John: [49:10] Can you say more about the data sources for the lake temperature data?

Jordan: [49:14] Yeah. We have been working on different workflows to get together lots of different sources for lake temperature data because the more we have, the better we can do at both assessing the quality of the models, and also building better models.

[49:37] Primarily, the widest coverage and most diverse lakes for temperature measurements come from the water quality portal, which is a joint project between the USGS and the EPA and combines both USGS and was discreet water temperature and all kinds of other water quality variables. Then all of the data in EPA stored, so that's 500 plus different contributors.

[50:12] Then, lastly, there's one other federal partner in there, which is USDA. That's our primary source of data. Additionally, we've gone after a couple data rescue efforts and Gretchen, in particular, with help from the Midwest Glacial Lakes Partnership for funding, worked with a student intern to digitize thousands and thousands of records that were in filing cabinets in Minnesota. I don't know if you want to add anything to that, Gretchen, but those are primary places where we get data from.

[50:53] We're also interested in doing more with remote sensing data, but presently the accuracy of, at least from satellites, remotely sensed surface-water temperature, it's not more accurate than we can model the temperature with these new methods. We're exploring different ways to use it to improve our models versus use it as a first-class water temperature observation.

John: [51:24] How is [inaudible] land cover such as local canopy cover and topography quantified and utilized in the lake temperature model?

Jordan: [51:33] Good question. I knew I had to skim over a bunch of these methods, which to me, I think, are fascinating because of my background in physical limnology. [laughs] I did skim over them because I thought they'd be a little in the weeds.

[51:49] In order to take what information we can get for canopy and turn that into a lake-specific number that we can use in a model, what we do is we create a buffer around the lake. It happens to be a 100-meter spatial buffer.

[52:06] Then we use that to mask out or to grab that portion of the National Land Cover data set to extract what the dominant land cover type is. Then we use a lookup table that gives us an estimated height for that.

[52:29] That's the way that we've been doing it for, I think, three years now. We did explore more complicated methods to get canopy heights using different remotely sensed methods. We've got a paper on that that I didn't show here. The end result of that is that doesn't end up improving our models versus this simpler method of using the National Land Cover data set with a height-based lookup.

[53:03] I think the details for that are covered in the Winslow et al, paper, the 2017 data paper in "Nature -- Scientific Data." That also includes a pointer to the first tristate version of this data release.

John: [53:21] Thank you very much.

Jordan: [53:25] Great. Thanks, all.

[53:25] [silence]

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