Karst, critters, and climate change: A multidisciplinary evaluation of karst species vulnerability to climate change

John Ossanna: To start things off, please join me in welcoming Abby Lynch, who is a research fisheries biologist with NCCWSC, who will be introducing our speaker today. Abby.

Abby Lynch: Thank you it's my pleasure to introduce today's speaker, who is Barbara Mahler, and she is research hydrologist with the U.S. Geological Survey's Texas Water Science Center.

Barbara received her master's and doctoral degrees from the University of Texas and joined the USGS following a one-year NSF-NATO Postdoctoral Fellowship in Montpellier, France.

Her research focuses on karst hydrogeology and aqueous and sediment geochemistry. Dr. Mahler is an associate editor for the "Journal of Hydrology," and has published more than 50 articles in peer-reviewed scientific journals.

She also enjoys backpacking, sculling, and spending time in France.

Welcome, Dr. Mahler.

Barbara Mahler: Thank you very much. It's really an honor to be invited to be part of the Climate Change Science and Management Webinar Series today.

I'm here just on behalf of a number of people, the co-authors on this presentation. They are a part of our multidisciplinary team. We have climate modeler, hydrologists and ecologists.

This type of multidisciplinary approach was necessary to tackle a question as complex as it is. We're focusing on karst landscapes today. That's why it's so complex. Some famous karst hydrogeologists once called karst the twilight zone of hydrogeology.

Karst landscapes, if you're not familiar with this term, these are areas where the underlying rocks are soluble. They're typically limestone and dolomite. Therefore, karst areas are characterized by springs, by sinkholes, disappearing streams and caves. It's one of the things that makes them mysterious to both the public and the hydrogeologists.

This is because in a karst subsurface, water moves through conduits that are dissolved out of the rock. This is very different from other types of aquifers where water is moving through very tiny pore spaces.

In karst aquifers, water can move extremely rapidly from the point of recharge to the point of discharge at a spring or a stream. Karst aquifers are often extremely productive, but they're very dynamic. They can fill and empty rapidly. Therefore, they reflect the effects of climate change at annual or even seasonal timescales.

Furthermore, the large cavernous porosity of karst provides unique ecological niches. The aquifer itself, within the aquifer, it can sustain life both above the water table, what we call troglobites, and below the water table, what we call stygobites or subterranean aquatic organisms.

The interior karst aquifers in the spring orifice, they can provide habitat for a lot of different rare and endangered species. I was surprised to learn that of the vulnerable or unparalleled species that are listed in the natural heritage database, half of them are subterranean. Meaning they're living in karst features, even though only four percent of these have federal status.

The motivation for our project then was, first, the fact that we have endemic and subterranean species that are relying on karst water resources and yet these water resources respond rapidly and nonlinearly to climatic variations. In times of drought, springs can dry up. In times of heavy rains, aquifer levels can increase by meters in a matter of hours.

It's not just discharge that can change. The chemistry of the water can change as well very rapidly, whether it's the temperature, the content of dissolved oxygen or the chemical quality of the water itself.

The question that we addressed with this project and what I'll be discussing with you this afternoon is what are the effects of projected climate fluctuations on karst ecosystems and the most vulnerable species?

Really, what we're looking at is a set of interrelated factors. We have climate, whether it's heavy rains or drought periods, which has an effect on the hydrology. Water levels and spring flow which, in turn, both of these can affect the flora and fauna. Now I'll put it a little bit more diagrammatically.

We started with global and regional climate models which we link. These provide data to directly assess the vulnerability of different species to climate change. Output like air temperature and precipitation and aridity.

We know that hydrologic factors also affect these species because these species live in karst areas where they live in springs, or they may live in spring fed rivers or within the aquifer itself.

The output from the climate models provide data, air temperature, precipitation data that we can use in site specific hydrologic models and then the output from the hydrologic models can also affect our decision-making process regarding the vulnerability of these different species.

They allow us to try and quantify, at least semi-quantitatively, species vulnerability to climate change. We examined the period from 2011 to 2050.

The two sites where we tried out this approach had some interesting similarities and differences. We investigated the Medicine Aquifer which is in the Black Hills region of South Dakota, and the Edwards Aquifer which is in the Balcones escarpment region of central Texas.

There are some interesting hydrogeological similarities between these two aquifers. In both areas, we have recharge areas exposed - that would be the darker colors on this diagram.

We have recharge that occurs in the Black Hills on the central uplift, and in the Edwards Aquifer to the west, it flows as stream flow over onto those recharge zones and it recharges the aquifer, and then it continues to flow down deep under overlying sedimentary rocks into the confine zone which is shown in the lighter pastel colors on this diagram.

There are also some important differences among these aquifers. For one, the Edwards Aquifer receives about 150 mm more precipitation on average over the course of a year than the Madison Aquifer, and it's about 15 degrees warmer as you can imagine, it's quite a bit colder in South Dakota than it is in Texas.

In both of these aquifers, we were able to take advantage of existing weather stations with long records of weather data. We examined two spring associated sites in the Madison Aquifer. One is the spring itself, and the other is a spring fed creek. In the Edwards Aquifer, we examined two springs and one well.

We have long discharge and water table historical records of data for these sites. Both of these aquifers support species that are dependent on the karst resources. We have vertebrates, we have invertebrates and we have a number of different plant species.

The Edwards Aquifer, the physical setting of this makes it one of the most biologically diverse regions in the nation. It's situated at the junction of the Great Plains and Coastal Plains physiographic provinces.

What we have is recharge occurring in the upland areas flowing along the Balcones escarpment over the recharge zone, and infiltrating into the aquifer, and then moving down deep into the confined part of the aquifer.

We have a lot of springs that occur in this region, because of the confluence of these two physiographic provinces, we have a large air temperature gradient over the escarpment, and higher precipitation over the escarpment area than over the rest of the region.

It's semi-arid in the west, and sub-humid in the east. We have a fairly rapid climatic gradient from west to east. We have some very extreme climate changes. We have droughts that can last from months to years. This area has also undergone some of the most extreme one-day duration storms that have been recorded in the world.

The typography is rugged. We have the plateaus dissected by canyons which create cool moist micro-climate from the north facing slopes. We have rivers, and streams, and isolated springs that can provide ecological niches for unique, relic and endemic species.

We also have wet caves which means that we can have stygobitic or a subterranean aquatic organisms living in the Edwards aquifer. The results: we have numerous endemic species - species that only occur in the average aquifer area.

The Madison aquifer is located in the Black Hills region. If you're wondering why it's called the Black Hills, it's because in the pre-Cambrian crystal and rock uplift either are a lot of dark pine trees that grow and they're a contrast with the golden grasses that grow out onto the plateau area.

This area is also where there are several ecological regions. We have a highland region, foothills region, and plateau region. As a result, in this area as well there's a warm direct climate that exhibits extreme variability over a small area because of elevation changes.

The precipitation up in the highlands is almost double what it is down in the plateau area. There is, like in the Balcones Highlands, there is extremely variable typography within the black hills. We have flowing streams that have caused deep canyons within rock faces and shaded valleys that provide special habitat for a number of different species.

In fact, the black hills region is the geographical limit of many North American species. What I mean by that is for northern species this maybe their southernmost limit and similarly, for southern species this may be their northernmost limit. There's this overlap of a number of different species in the Black Hills region.

As a result, there are isolated populations, and varieties, and sub-species of a number of different organisms. Interestingly, there's little endemism at the species level. It's considered rare to non-existent in the Black Hills region.

There's only two endemic troglobitic species described and those stygobitic species. There’s quite a bit of biological diversity, but is all associated with surface water, it's not associated with the aquifer.

Part of the reason is because the caves are dry. There are no cave streams in which aquatic organisms can live. The water in the aquifer itself has a very low microbial biomass.

We needed to take an innovative approach to model the complexity of these karst aquifers in these settings, because we have topographic relief over a relatively limited scale and climatic changes. We also have very rapid hydrogeologic responses which means we need to be able to model the hydrology at very short time steps.

The approach we used was to link a global climate model with a regional dynamical climate model. The global climate model that we used was a Community Climate System Model, or CCSM3, and we linked that using initial conditions and boundary conditions with a regional model, the Weather Research and Forecasting Model or the WRF Model.

Regarding the CCSM3 model, this is an atmospheric ocean global circulation model with simulations available for 1870 to 2100. We chose to use an A2 emissions scenario. This is an emission scenario that favors economic considerations over the environment and individual responses over community responses.

We chose the A2 scenario because it aligns with most previously published regional climate model simulations, and because carbon dioxide trends have generally followed this highest emission scenario. The Co2 measurements were available for the A2 emission scenario for 1970 to 1999.

We also chose the CCSM3 simulation that produced a six-hour time step which is required for the WFR Model. We did consider a couple of other global models. We considered The Geophysical Fluid Dynamics Laboratory model, and The Canadian Centre for Climate Modeling and Analysis general circulation model.

To help in our decision we compared output for the Great Plains for the three different models. The CCSM3, and the other two models. We compared that to measured data produced by the Prism model.

The prism data, the measured data, is shown here in the solid black line for air temperature, the solid red line is the CCSM3 modeling. You can see that we have a pretty good agreement.

We're not trying to get exact agreement, what we're looking for is the same thing and amount of variability and that the two other models showed in the stapled and dash lines have about a three degree code bias.

If we look at precipitation down below, we see pretty good agreement between the Canadian model and the measured data which is in black. Then our CCSM3 shows something of a wet bias relative to the measured data. Then the third model which is Geophysical Fluid Dynamics Laboratory model shows more of a wet bias.

Given all these considerations, we chose to use CCMS3 because it had the best skills for simulating air temperature, and it still retained a moderate skill for simulating precipitation.

Moving on to our regional climate model, a short time step and a high level of special detail were crucial for modeling climate and hydrology in karst and particularly, in our two study areas.

Our climate modeler, John Stamm, adapted the WRF Model through a 36 km grid spacing based on the initial and boundary conditions from the CCMS3 global climate model.

He computed two simulations. One from 1981 to 2010, that's a continuous simulation of contemporary climate. One for 2010 to 2050, that's a simulation of projective climate. We could use the contemporary climate projections to compare to existing data and do whatever bias adjustments we needed to do.

We have a three hour-time step for our output although the computed time steps are much shorter which is excellent, because we need that type of really small time set for the hydrologic model.

Then this three-hour time step output can be integrated to daily and monthly values which are used for the analysis directly with the endangered species, or with the species under consideration.

The WRF Model atmospheric variables include temperature, pressure, moisture, and winds at multiple levels in the atmosphere. The hydrologic variables include precipitation, evaporation, and soil moisture, and runoff at the land surface.

We were able to compare the WRF Model output for contemporary climate to prism data, and do a biased adjustment for temperature and precipitation. Then following that bias adjustment, a continuous series was constructed using weather station data for our three weather station to 2010 and then projected data out to 2050.

What do we expect to see looking out to 2050? We used Kendall's tau nonparametric trend test to look at some of the output for the projected climate based on the WRF model. What we're seeing here are data for our three sites or our three areas. Boerne, Texas Weather Station to the left and then the two South Dakota weather stations on the right.

On the top, we're looking at air temperature. The red is the maximum, or its the mean of the daily maximum, the black is the mean of the daily mean and the blue is the mean of the daily minimum. What we see is that for air temperature, for all three weather stations, we have a statistically significant upward trend in projected temperature from 2010 out to 2050.

If we look at precipitation, which is in green, we see a statistically significant downward trend for our Texas Weather Station, but no significant trend for the two South Dakota weather stations.

We can also look at these climate projections across a year. We have winter starting on the left hand side of the graph, going through December and then back to winter at right hand side of the graph. Again, we have the Texas Weather Station on the left and the South Dakota weather stations on the right.

Looking at temperature, what we're projecting for Texas, if we look at this via the dotted lines relative to the solid lines, higher highs in the summer. Something to look forward to if you live in Texas. We're expecting to see higher lows in the spring and winter.

If we look at South Dakota, we're looking at higher highs in the spring time which could affect this timing of snowmelt. For the Custer Weather Station, we're looking at higher lows across the year. At the Lead Weather Station, we're looking at higher lows principally in the spring time.

If we look at precipitation in the lower graph, mostly what we're seeing is a predominance toward more precipitation in the fall and a little bit less precipitation in the summer, particularly in South Dakota. The increased spring precipitation that we see in South Dakota may also work with that increased temperature to enhance spring melt of snowfall.

We're going to put all of these data together, the climate information and hydrology, and see what we get. Our hydrologic modeler, Andy Long, constructed site-specific convolution models. At each site, he took precipitation and air temperature, and used that to model water discharge at the springs and water level at the well.

The model simulates two processes in series. The process of precipitation becoming recharge, and the transition of recharge into a hydrologic response.

The model precipitation becoming recharge, he used the output from the WRF model, the precipitation and air temperature output to estimate a daily soil moisture index. Then daily recharges computed as a product of precipitation and that daily soil moisture index.

That produces a recharge signal. That recharge signal is then translated by the aquifer into a response which could be water table level or it could be spring discharge.

If you think of hitting each of these signals with a function, it creates a response. That function that's chosen is called an impulse response function. It could be a lognormal function or an exponential function.

You can think of this function as the system memory. It's the same idea as a unit hydrograph. At the site, each of these signals and responses is superposed one on another. What we might see at a spring as a discharge response would look something like the sum of these curves shown here.

This method actually works really nicely. Here's a result that we can see for...that graph didn't come up. I had an example of how well the model results fit the discharge at Spearfish Creek, but we'll see a few more of those results in another graph.

Groundwater flow in a karst aquifer...looks like we're missing a little bit of graphics here too. I'll just describe to you what you ought to be seeing.

If you imagine a karst aquifer, it has areas of fast flow in conduits and it has areas of slow flow through fractures and even micro-fractures. In karst, a single impulse response function isn't sufficient. Andy used one impulse response function for conduit flow that shows a very fast response and one for fracture flow that shows a much longer, more drawn out response and he superposed them.

Another complexity of karst is that it often has extreme vertical heterogeneity. In other words, we might have a conduit network located at one level but not at another. Maybe that conduit network is accessed when water levels are high, but not when water levels are low.

In all, at each site, Andy could use as many as four different impulse response functions. He calibrated his responses using historical data and validated them to existing historical data and then projected discharge at each site discharge or water level out to 2050 based on the air temperature and precipitation output from the WRF model.

Here's the type of IRF or Impulse Response Functions we used for fast flow conduits and here's what he used for flow in the fractures. What might we expect to see in terms of the hydrogeology?

Here's the response of the Edwards Aquifer sites. We have our two spring sites on the top and then the index well down at the bottom. That solid brown line is measured discharge or water level and the stippled blue line are the modeled response.

First of all, we're seeing a pretty good match between our model and the existing data. At the springs, we're seeing a slight but significant downward trend in discharge. At the well, we're seeing an even more pronounced downward trend and water level.

This is of interest because we're seeing water levels between 2040 and 2050 that are projected to be even lower than the drought of record during the 1950s.

This type of information, just the hydrologic projections, are actually of a lot interest to water managers for nothing else because the Bear County index well is the well upon which the City of San Antonio bases its decision on pumping and water restrictions and regulations.

In contrast, if we look at the Madison Aquifer sites, we don't see a statistically significant trend in either direction in terms of spring flow. We're not expecting to see a big difference in spring discharge or stream discharge at the Madison site.

We see what affect our projected climate is having on hydrology. Both climate and hydrology can have an effect on the ecology at the sites that we're considering.

To try and characterize the vulnerability of different species at these sites to projected climate change, we used a tool developed by NatureServe called the Climate Change Vulnerability Index. It considers a large number of different factors that might affect a species vulnerability.

It considers several factors considered to be characteristic of climate exposure itself. This is the character magnitude and rate of change of climatic parameters. Some direct factors are things like projected air temperature change or projected water temperature change or change in aridity index.

It also considers some indirect factors such as the existence of barriers to range shift or the potential human response to climate change such as increased pumping that might in turn affect the vulnerability of the species.

It also considers the sensitivity of the species. For example, the physiological, biological, and ecological factors that are particular to a species and also the ability of the species to cope with climate change effects.

This might include dispersal means. Can the species get away from the site? If it's a plant, can it disperse its seeds at a distance from the site into a different region?

It might include also the reproductive response to projected air temperature change. OR even the vulnerability of a species' prey species to climate change.

Scores are assigned to six measures of exposure in 16 measures of sensitivity and adaptive capacity. More than one score can be assigned to each measure. This might occur, for example, if there are studies that have different results regarding a particular factor.

As a result, we get these mixed ranges of scores on vulnerability. To try and determine to settle on a score, a Monte Carlo approach was used. Our ecologist, Amy Symstad and Mary Poteet, ran a hundred simulations with each simulation collecting a single vulnerability score for each factor.

Then the distribution of those scores is used to calculate a statistical confidence in the final ranking, whether it's more confident or less confident in terms of its vulnerability ranking.

Amy and Mary did come up with a couple of innovations to NatureServe's original climate change vulnerability index. One of the first was that rather than using the climate model provided by NatureServe, they used the climate model that had been developed for our project by John Stamm. This had shorter time steps and a more refined spatial scale.

Another important innovation was to incorporate the hydrologic projection. The specifically projected flood intensity and frequency and projected stream and spring flow were worked into the climate change vulnerability index.

That's because things like flood intensity and frequency can affect habitat, and projected stream and spring flow affect water temperature and dissolved oxygen. These are important in the context of the species' physiological thermal niche.

How is this applied? Let's take a model species. *Eurycea waterlooensis* or the Austin blind salamander, this is a federally-listed endangered species that is endemic to the Barton Springs complex in Austin, Texas.

As far as exposure, the climate change model projected an air temperature change of 1.65 degrees out to 2050 and a percent aridity index change of about 0.1. In terms of sensitivity and adaptive capacity, one of the factors that's considered is the distribution of the species relative to natural barriers to range shift.

This is an endemic stygobite that occurs in only four springs. This factor was scored as greatly increasing the species' vulnerability.

Another factor is distribution relative to anthropogenic barriers in range shift. *Eurycea waterlooensis* lives in springs that are no longer connected because of human alteration in the form of dams, pipes and swimming pools. This factor was also rated as greatly increasing its vulnerability.

A third factor is the impact of human response to climate change on a species. In the Edwards Aquifer, we're expecting that warmer temperatures and decreased water level will lead to increased pumping, which might somewhat increase or increase the vulnerability. Here's a case where the species was given two scores for a factor.

For another factor, the habitat, mortality or reproductive sensitivity to projected air temperature change, that will cause water flow to decrease and will increase water temperatures. This was scored as increase or greatly increase vulnerability. Again, two scores for one factor.

Another factor is species' restriction to uncommon geologic features. This species is restricted to these spring outlets. This was scored as increasing vulnerability.

The final factor, as an example, is species' dietary versatility and the vulnerability of its prey species to climate change. Here, we don't know the answer. We don't have any documentation for this. This was scored as neutral. The final score for this species was moderately vulnerable.

First, our colleges had to determine what species to consider. They used two criteria. The first is conservation concern.

Is a species threatened or endangered at the state or federal level, or is it a management indicator species, does it have a natural heritage ranking or is it a recently discovered species? Any of those qualified it as of conservation concern.

A second criteria is whether it is dependent on karst geology or hydrology. Does it spend its life cycle largely limited to springs and streams? Does it live in a moist cave or a wetland that is fed by a spring? Does it live in the aquifer itself? Is it an endemic karst species? Any of these would classify it or qualify it as being dependent on karst geology or hydrology.

It turns out, I said the Edwards Aquifer was a biologically diverse region, there were 231 species that qualified. Of those, 14 were chosen for this particular categorization of vulnerability. There were 25 species in the Madison Aquifer that fit the criteria. We chose eight for analysis here.

Why did we narrow it down to these 14 Edward species and eight Madison species? First of all, these species span a range of taxonomic groups. They include mammals, birds, and plants.

Secondly, they're all associated with the hydrologic features that we simulated, the spring and spring-fed creek in the Madison and the two springs and well in the Edwards.

Finally, for all of these species, we had ecological information that was sufficient that we could actually use the vulnerability assessment tool.

Taking a look at our results, what does the future hold? Only one species was rated as highly vulnerable. This is a different salamander. This is *Eurycea sosorum*, the Barton Springs salamander, which also is a federally-listed species that lives in Barton Springs in Austin, Texas.

This was rated as highly vulnerable because of natural and anthropogenic barriers to range shift, the fact that we're predicting increased pumping. We know that this species has sensitivity to bloat dissolved oxygen related to low flow and higher water temperatures. It's an endemic species. We also know that it has low genetic variation.

Another couple of examples. These are listed as moderately vulnerable. There are an additional nine species in the Edwards listed as moderately vulnerable and four in the Madison that were listed as moderately vulnerable.

Some interesting examples here and character criteria that caused them to be listed as moderately vulnerable. The autumn willow, for example. This species has low adaptive capacity because of its small population. It requires a very specific habitat. It's sensitive to high temperatures.

On the other hand, it was only moderately vulnerable because these characteristics are countered by its high dispersal ability. It has wind-blown seeds and also a projected increase in spring flow that feeds its restrictive fen habitat.

Another example is the Black Hills mountain snail which also has a small population, requires a specific habitat and is sensitive to high temperature. Seven factors had multiple scores which means, in fact, we almost had too much information because there are studies that provide conflicting information which led to great uncertainty.

There were other species like the Bear Lodge Mountain jumping mouse which was scored as not vulnerable because it's not restricted by high air temperatures, and it has a broad habitat and dietary tolerance.

What we concluded from this initial try at using this approach was first that it seems as though endemic and fully-aquatic species are more likely to be vulnerable to climate change. Seventy-five percent of the Balcones Escarpment, the Edwards Aquifer species are endemic and none of the Black Hills species are.

What this means is that these species, because they're endemic, have a highly restricted range and habitat. Many of the aquatic species have a low thermal tolerance. It also became clear that the dry caves and extremely low microbial biomass of the Madison Aquifer led to a lack of stygobitic and endemic species.

Another conclusion we came to is that, including the hydrology allowed us, we thought, to provide more realistic vulnerability analysis. In fact, when we included these hydrogeological considerations, it resulted in an increased vulnerability score for 12 of 16 of the Edwards Aquifer species or 75 percent of those species.

Interestingly, it decreased the vulnerability scores for some of the Madison Aquifer species because it looked like we were going to continue to have perennial spring flow and stream flow. Even though the temperatures were increasing, these species were still going to have a consistent resource to rely on.

We felt that the detailed climate and hydrologic data that we were able to get with these new and revised models provided an improved evaluation because it gave us a short time step and it gave us a type of information we needed for temperature trends over a small area and a strong climatic gradient that we see over small distances in both areas.

On the other hand, we used only the A2 emission scenario and only the CCSM3 model. Using different emission scenarios and different climate models might provide different results or at least allow us to confirm the robustness of the results that we have.

What we came out of this really believing is that time series data is really important. Long-term historical data for air temperature, precipitation, but also for discharge at some of these karst features is critical. We were really lucky in these two aquifers to have such detailed records. It underscores the value of investing in these types of data.

It also shows the value of detailed biological information. If we don't have the information on these species, we can't use any type of vulnerability index tool because we don't have the answers to the types of detailed questions that are being asked.

All in all, we felt that this approach linking climate models and hydrologic models and then using both of those to provide data or input for a climate vulnerability index tool that this provides valuable information for resource managers. Both those who are water resource managers who need to better understand how their resource might be changing in the coming decades, and also for state, local, and federal agencies that are managing species and the karst habitat.

There are two USGS reports that have resulted from this project. Both of these are available online. There is a scientific investigations report first authored by John Stamm. This provides many more of the details than I've been able to share with you in the presentation today.

There's a four-paged summary of the SIR available as a fact sheet. This would be really handy to be able to share with resource managers or even to be able to use in an academic setting.

We also have some additional journal publications that have been the result of this work. In particular, if you're interested in learning how to use or create a site-specific hydrologic convolution model like Andy Long did, I would strongly suggest that you take a look at these two publications or contact Andy directly.

That is the conclusion of my presentation. At this time, I would be happy to answer any questions that you might have.

John: Thank you, Barbara, for your presentation. First question comes from Than. I hope I pronounced that right. "Is karst water temperature sensitive to air temperature changes? Do your hydrological models account for this spatial/temporal variation."

Barbara: That's a really good question. The short answer is yes. In fact, all groundwater is sensitive to air temperature changes. Over fairly long spatial scales. Groundwater tends to reflect the ambient air temperature and ambient annual air temperature, but in karst we see much more rapid changes in water temperature. We see warmer temperatures in the summer, cooler temperatures in the winter, but we also see the effects of rapid recharge of that.

If we get a big warm rain in the summer time, we'll see the water temperature of the spring increase. If we get a cold rain in the winter, we'll see the water temperature decrease. This can happen over a matter of hours.

In this particular model, we didn't model water temperature. We only modeled air temperature. However, Andy Long and I have been working on a convolution model that models water temperature from the springs using air temperature as an input. He's been very successful at matching that. That's a very promising direction that we can go.

John: Next question is from Ryan Boyles. "How difficult would it be to add additional GCMs or use existing downscaled projections? I suspect the results are very sensitive to the single GCM and scenario used."

Barbara: Ryan, you're probably right that there is quite a bit of sensitivity to the scenario used and that we might see something different if we used a different GCM. It would be fairly labor-intensive to try out some different GCMs or different projections.

I don't know if we can get John Stamm. He did call and he's our modeler. John, are you able to unmute yourself and address that question?

John Stamm: Hey, can you hear me?

Barbara: Yeah.

John: That is a great question. One of the things, if we're able to move forward on this, is that the GCMs these days are getting very close to the resolution, the 36-kilometer resolution that we use. They're getting down around 50-kilometer resolution.

At that point, you're able to resolve things like the Black Hills. They'll actually appear on there. You might see the Edwards Plateau. New GCMs that come out actually lend themselves much better to using this approach.

Back when we were doing this work in 2012 to 2013, a lot of the models just didn't even resolve the Black Hills at all. It was difficult to use them. There really weren't that many downscale models at that time.

John: The next question is, "Do you have any suggestions or ideas about including evolutionary potential for any of the karst species?"

Barbara: I'm guessing that this question relates to whether that potential might be worked into the climate vulnerability index tool. Clearly, that index tool can be adapted for any user. That is something that we might want to consider.

We do have some indication that, for example, the salamanders can evolve. The *Eurycea sosorum* is thought to be related to *Eurycea nana* which is in different aquifer system to the South. They are now genetically distinct. I think that they were originally thought to be the same species.

That's something that could be considered. Either Mary or Amy, are you on the line? Could you address that question in any more details?

Amy: This is Amy. Can you hear me?

Barbara: I can.

Amy: The CCVI does include…one of its things that it scored is genetic potential or basically how genetically diverse is the species. That is included in the vulnerability index. That information is often very difficult to find for a species. It actually ends up being an optional add-on in the CCVI.

Barbara: You need to have that type of information on the species to be able to include it in the analysis.

John: Next question is also from Ryan. That might be actually a statement. It does look like a statement. He's talking about different ways. With MACA and LOCA downscaled projection, you can get greater less than a 10-kilometer resolution across dozens of GCMs and that leads to emission scenarios.

This might help characterize the uncertainty and help start thinking about adaptation planning. It would depend on how sensitive the hydro model is as to climate. The agreement between modeled and observed hydrology is impressive.

John: This is John. There's a lot of products out there right now that we could use and apply this methodology. This, to some extent, was a proof of concept paper. It's more than that, but it's our first time trying to do all these linkages. Barbara may be able to discuss a little bit more along those lines.

Barbara: John, that's exactly right that we wanted to see how effectively we could link the models and pull in the hydrology and to what degree that might affect the vulnerability evaluation.

Clearly, this can be expanded. I'd love to see this maybe done in more detailed...in these areas, but also apply to other areas where there are species of concern.

John: We have a question from Eduardo. Have the modelers considered using NEXRAD precipitation to model the spring discharge response?

Barbara: Andy, are you on the line? You want to handle this one?

Andy: Sure. Can you hear me?

Barbara: Yes.

Andy: These models were site-specific. It's a time series model. It's not a distributed model. We just used an appropriate weather station that was in the area of the spring discharge or water level that we were trying to predict and then calibrated the model that way.

For the projection for the future, we used the WRF model output for that same location. We could've used NEXRAD also, but we felt the station data or the model calibration was better.

John: Right now, I don't see any questions. I would like to just, once again, thank Barbara and everyone who participated.

Barbara: Thank you very much.

Transcription by CastingWords