Linking groundwater and climate to understand long-term lake level fluctuations in Wisconsin

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Water level changes in lakes can have substantial socio-economic and ecological consequences. Understanding long-term variations in water levels for seepage lakes (i.e., closed-basin systems that lack surface inflows or outflows) requires consideration of the role of groundwater, climate and other patterns in driving lake level dynamics. Natural resource management of stream ecosystems explicitly accounts for streamflow variability, and similar frameworks will also advance groundwater and lake management. However, few Wisconsin lakes have long-term water level records, hindering informed management decisions. The objectives of this project were to first compile historical water level and climatic data into a publicly available database, then analyze the spatial and temporal coherence of historic water levels. Next, we used the above information to model historic lake levels and characterize hydrologic regimes for all seepage lakes.

We compiled historical lake level, groundwater level, and climate data from multiple governmental agencies and academic institutions. The final lake level dataset includes 501 seepage lakes and 535 drainage lakes with a total of 342,319 observations dating from 1900 to 2015. We invested substantial effort in linking disparate data sources for the same lake together by comparing datums and transforming data when possible. The groundwater level dataset includes 964 monitoring wells with about 400,800 observations spanning 1929 to 2015. Both data sets were published through the Environmental Data Initiative. Precipitation data were already available online (PRISM) but were essential for subsequent modeling efforts. Evaporation data came from a model developed by Jordan Read at USGS.

We investigated the spatial and temporal coherence of water levels across Wisconsin to inform our lake level modeling approach and learned that emerging spatial patterns are a result of spatial heterogeneity in precipitation. From 2001 to 2015, lakes and wells in northern Wisconsin fluctuated in unison and opposite that of southern Wisconsin. Whilst northern Wisconsin experienced drought *c.* 2009, southern Wisconsin experienced extreme flooding. Thus, instead of developing regional lake level models based on the coherence analysis, we developed statewide models with precipitation as the major driver of water level fluctuations.

We reconstructed historical water levels using two different approaches. The first approach relied on the strong correlation between water levels and precipitation and the second approach built a mechanistic-based model using both precipitation and evaporation data.

The first model predicted lake level fluctuations using the cumulative deviation of monthly precipitation from an 8-year rolling mean (cmdev) as the sole predictor variable. Rather than simply representing the most recent precipitation events, this metric accounts for memory in the system. We fit hierarchical linear models whereby the slope between cmdev and lake level was fit for each individual lake and for the population of lakes. The model performed very well, with a slope between cmdev and lake level of 1.2 across all lakes and individual lake slopes ranging from 0.5 to 4.

Given the variation in slopes observed between lakes, we attempted to better understand and predict which lakes would respond more or less dramatically to changes in precipitation. We fit a multiple linear regression model to predict slope from a variety of lake and watershed characteristics. The final model used the difference between lake elevation and maximum watershed elevation, percent riparian forest, and the soil Darcy value to predict the slope and explained 49.1% of the variation in the relationship between cmdev and water level. This model enabled better lake-specific water level predictions.

The second model was based on a water budget for a seepage lake, with the change in lake level resulting from incoming precipitation, outgoing evaporation, and net groundwater flux. The model used observed lake level and precipitation data and modeled evaporation data to solve for stage-specific groundwater outflow (ϭ) on a one-year time step. This model performed well overall. Among the 20 lakes with sufficient data, groundwater outflow ranged from 22 – 43 cm/yr (mean = 35 cm/yr).

As with the empirical approach above, lake-specific ϭ values were extrapolated to seepage lakes that lacked water level observations by developing a multiple linear regression model to predict ϭ. The best model explained 72.3% of the variation in lake-specific ϭ values using lake elevation, lake maximum depth, and lake conductivity as the only predictor variables. Average groundwater outflow was 36 cm/yr (range 24 - 48 cm/yr) in the 312 seepage lakes for which we extrapolated lake-specific ϭ.

Hindcasting water levels over long periods of time (since the 1920s) provides an opportunity to contextualize water levels within a lake's hydrologic regime instead of simply within the available record. Across all seepage lakes with precipitation-based water level predictions, 20% of the time lake stage equaled or exceeded 26 cm above the long-term average (range 9 to 54cm) and 70% of the time it equaled or exceeded -19 cm (range -45 to -6cm). Thus, on average for lakes considered in this study, water levels were typically +/- 0.25m 50% of the time for any given lake.

This project greatly enhanced Wisconsin's understanding of lake and groundwater level fluctuations in Wisconsin and will benefit lake management. Not only have we compiled and made publicly available the most comprehensive lake and groundwater level database, we now have two models that effectively hindcast water level fluctuations in seepage lakes. We used these models to hindcast lake levels on 316 seepage lakes without water level data and can now better describe the expected magnitude of lake level fluctuations in Wisconsin. These models may also be used for specific management or research questions where lake level fluctuations are critical but have not been observed. Finally, we learned that precipitation is the main driver of lake level fluctuations, with lake landscape position, soils and forested lands, lake morphology and lake conductivity influencing how dramatically a given lake will respond to changes in precipitation.