Appendix E –Central Sands Lakes Study Technical Memorandum: General Lake Model

Evaporation from the surface of a lake is a significant component of a lake's water budget. We needed to estimate lake evaporation rates for our study lakes because the Central Sands Lakes Study (study) covers a period when lake evaporation rates were not directly measured. The study also includes hypothetical scenarios that required estimated lake evaporation rates.

For an initial estimate of lake evaporation, we used the unmodified Hamon equation. To determine the efficacy of the Hamon equation, we used the General Lake Model (GLM) to simulate the thermal structures of the study lakes, which produced a correction factor to the Hamon equation as a simplified estimator of lake evaporation rates. The GLM can also be used to understand lake levels and stratification within the lakes.

Hamon Equation

The Hamon equation (Hamon, 1961) is an estimator of daily open water evaporation requiring only latitude and the average daily temperature. The Hamon equation is an appealing tool for lake evaporation estimates because it requires few inputs and is easily calculated. It is a tool that has been used for other lake hydrology studies in Wisconsin (Leaf and Haserodt, 2020). The equation uses latitude to estimate the maximum daylight hours for each day, and the average daily temperature to estimate the daily saturation vapor density. The maximum daylight hours and saturation vapor density can then be used to estimate the daily open water evaporation. For a detailed explanation of the Hamon equation, see Appendix 2 in Harwell (2012).

General Lake Model

The GLM (v. 3.0.0) is a process-based one-dimensional model that simulates the thermal structure of a lake using a Lagrangian layer scheme and a daily timestep with daily flows and meteorological conditions as inputs and outputs (Hipsey et al. 2019). Other hydrology studies in Wisconsin have used the GLM in conjunction with groundwater flow models for simulation of hydrodynamics in shallow lakes (e.g., Robertson et al., 2018). The GLM is based on mixing process parameters, and site-specific calibration is typically not necessary (Robertson et al., 2018), although a few parameters can be changed for modest model improvement. We ran the GLM during the history-matching period for the groundwater flow model from 2012 to 2018 (Fienen et al, 2021).

GLM Inputs

To assess model performance, we used data such as the physical characteristics of the lake (depth, stage-volume relationships) from this study (Voter et al., 2021) and lake stage. We input daily meteorological data from the North American Land Data Assimilation System (NLDAS; Mitchell et al., 2004). Because the study lakes are seepage lakes, there were no surface water inflows or outflows to specify. Groundwater fluxes were supplied by the groundwater flow model developed for the project (Fienen et al., 2021). We ran the groundwater flow model at a monthly timestep, so changes in groundwater flux into and out of the lake occur as a step function at the end of each month. To smooth out these flux inputs, the monthly flux estimates were transformed to daily flux estimates with a natural cubic spline with a minimum flux of zero. Additionally, we supplemented the groundwater flux values with groundwater temperatures from the USGS monitoring well PT-24/09E/13-1573, accessed through the National Water Information System (NWIS) database (USGS 2016). This monitoring well is within the Central Sands model domain and is one of the few USGS wells that has temperature data. We supplemented missing temperature data with average temperatures from the same day of other years.

GLM Parameters

We left the parameters within the GLM as default values (as given in Hipsey et al., 2019) except for: the maximum number of layers, the minimum and maximum thickness of layers, and the minimum volume per layer. Because these lakes are so shallow, we reduced the minimum layer thickness to 0.015 m (Long, Plainfield) or 0.1 m (Pleasant), and adjusted the minimum volume (0.025 m^3 for all three lakes), maximum thickness (0.36 m for Plainfield, 0.25 m for Long and Pleasant), and maximum number of layers (120 for all three lakes) to allow for model convergence. We also adjusted the light extinction coefficient (Kw) based on Secchi depth readings taken as part of the study (Voter et al., 2021).

GLM Results

Below, we share the results for lake stage, lake mass balance, and lake thermal stratification, which are used to determine how well the GLM is performing at simulating the lakes.

Pleasant Lake

The GLM initially modeled Pleasant Lake stages much lower than measured values. It was determined that the most likely cause of misfit was that MODFLOW-derived groundwater fluxes were off by as much as 25%. The groundwater inflow was increased in GLM by a factor of 1.25, as the hydrologic setting of the lake would likely allow for more inflow than outflow, given the proximity of nearby spring-fed streams immediately downgradient of the lake. After making this change to groundwater inflow, the modeled and measured stage values line up reasonably well (Figure 1), with a root-mean-square error (RMSE) of 0.07 meters.

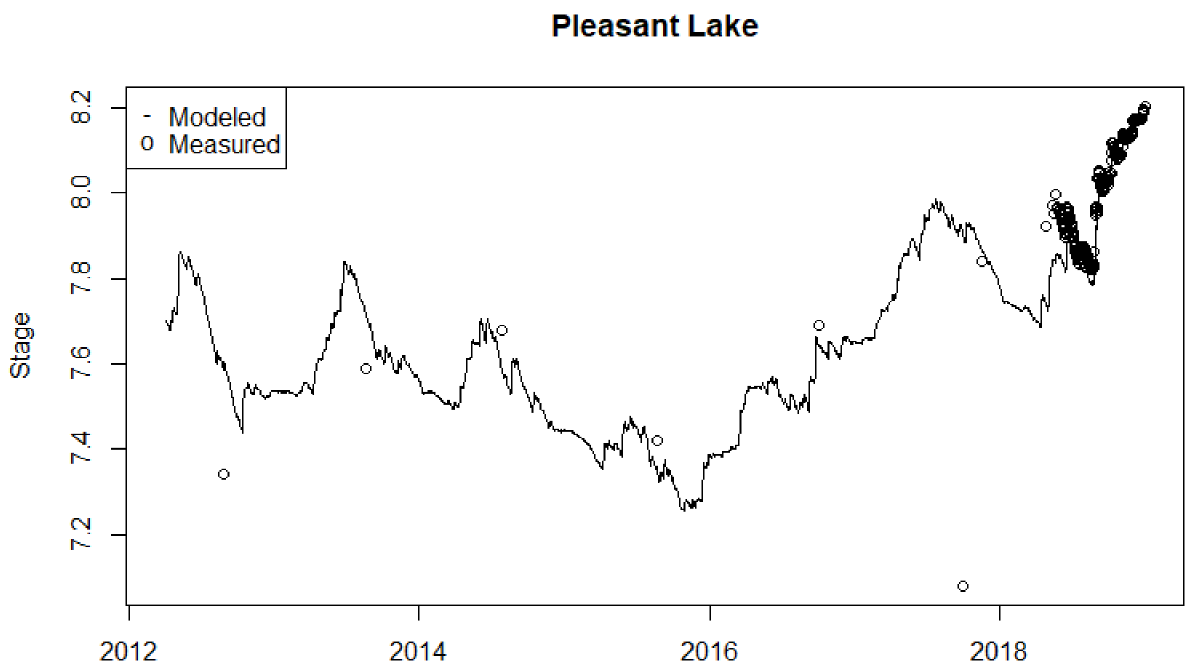

Figure 1. Modeled and measured lake stage values, in meters, for Pleasant Lake**.**

The mass balance for Pleasant Lake shows that precipitation is typically the largest inflow to the lake, followed by groundwater inflow (Figure 2). Evaporation from the lake surface is typically the largest flow out of the lake, with the highest evaporation rates during summer. Groundwater outflow increased later during the model period, a period corresponding to increased lake stages and increased groundwater flow into the lake.

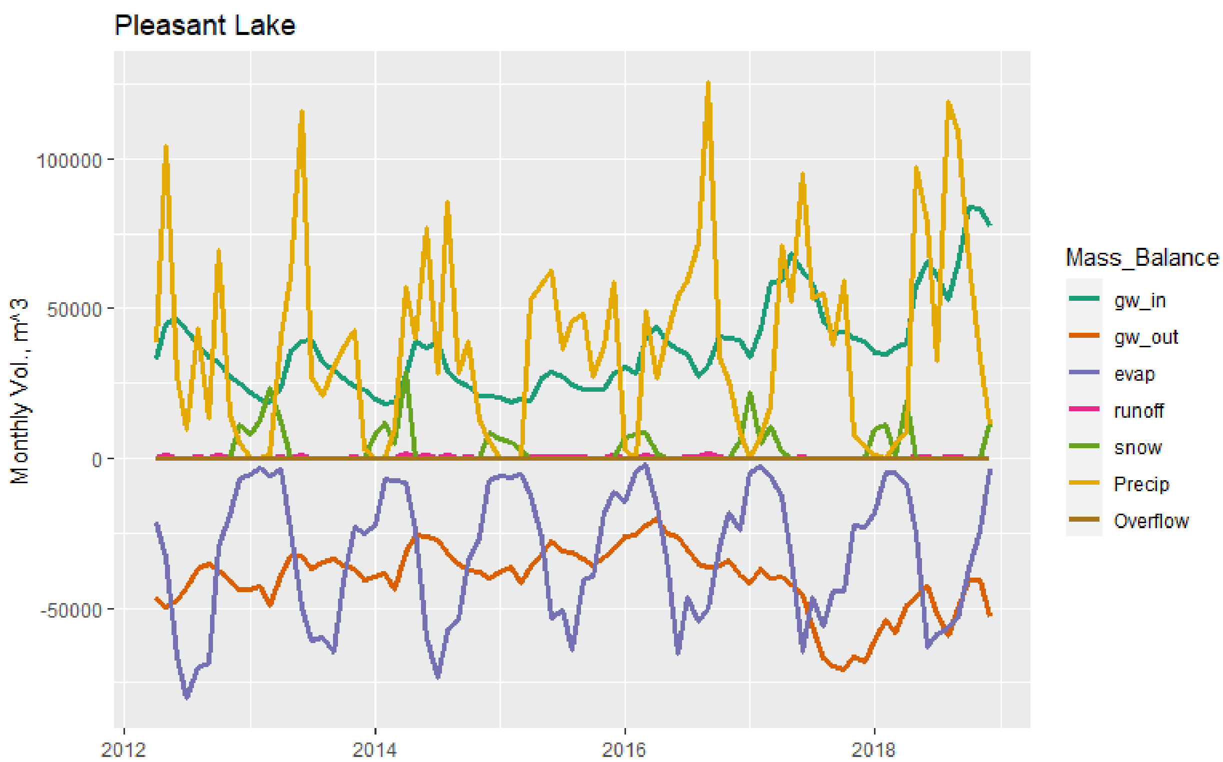

Figure 2. Modeled lake mass balance for Pleasant Lake**.**

The modeled thermal stratification of the lake shows Pleasant Lake stratifying every year with yearly mixing events (Figure 3), and the thermal profile generally aligns with temperature profile data from 2018, the only year for which data is available.

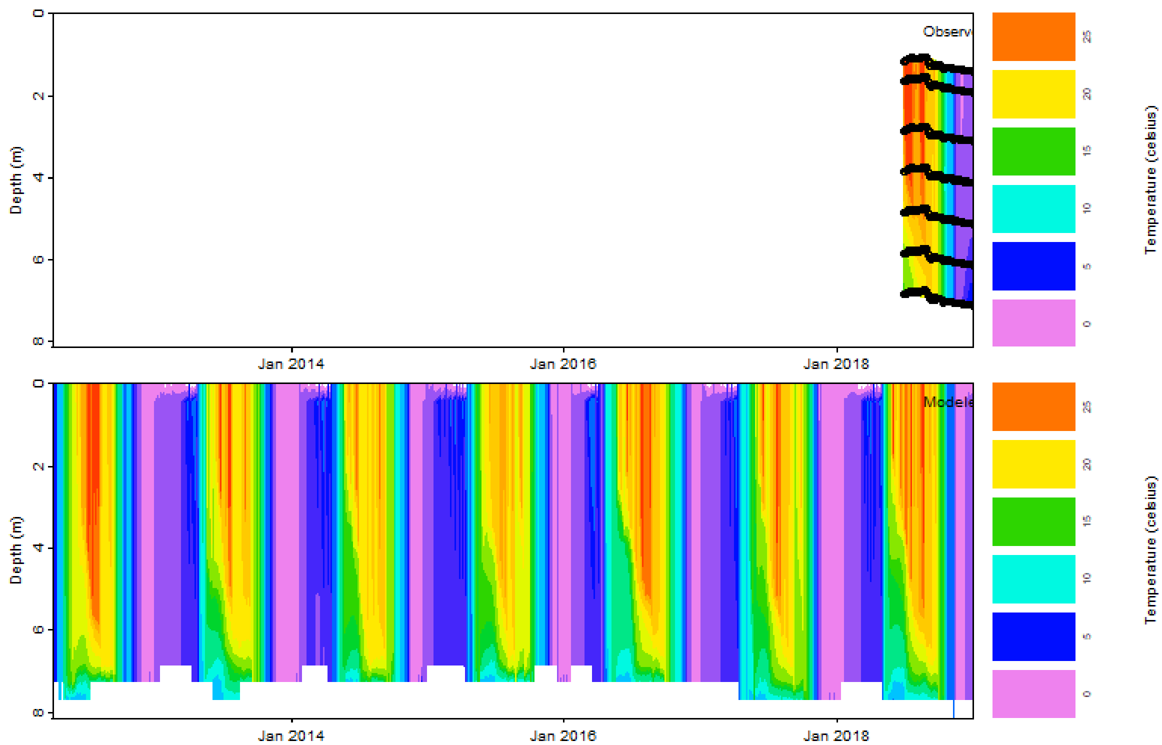

Figure 3. Modeled (lower panel) and measured (upper panel) lake stage thermal stratification for Pleasant Lake. Black dots on the upper panel are observations points.

Long Lake

Long Lake did not need any correction factors to groundwater inflow or outflow. The modeled stage values are in general agreement with measured stage values (Figure 4), with a RMSE of 0.2 meters.

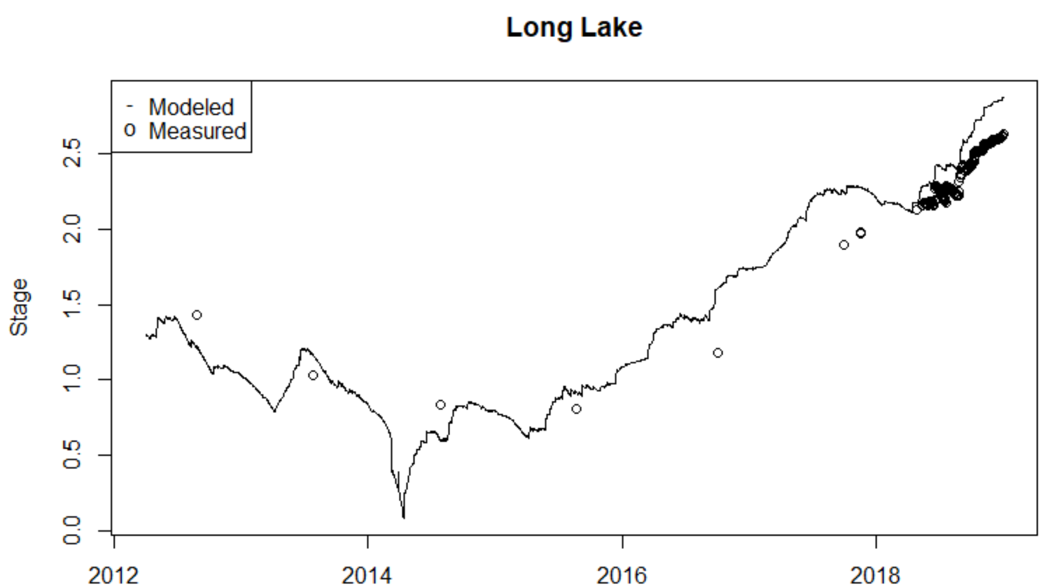

Figure 4. Modeled and measured lake stage values, in meters, for Long Lake.

The mass balance for Long Lake shows that the groundwater flow into the lake and precipitation are of similar scales, and groundwater outflow is typically the largest flux out of the lake (Figure 5).

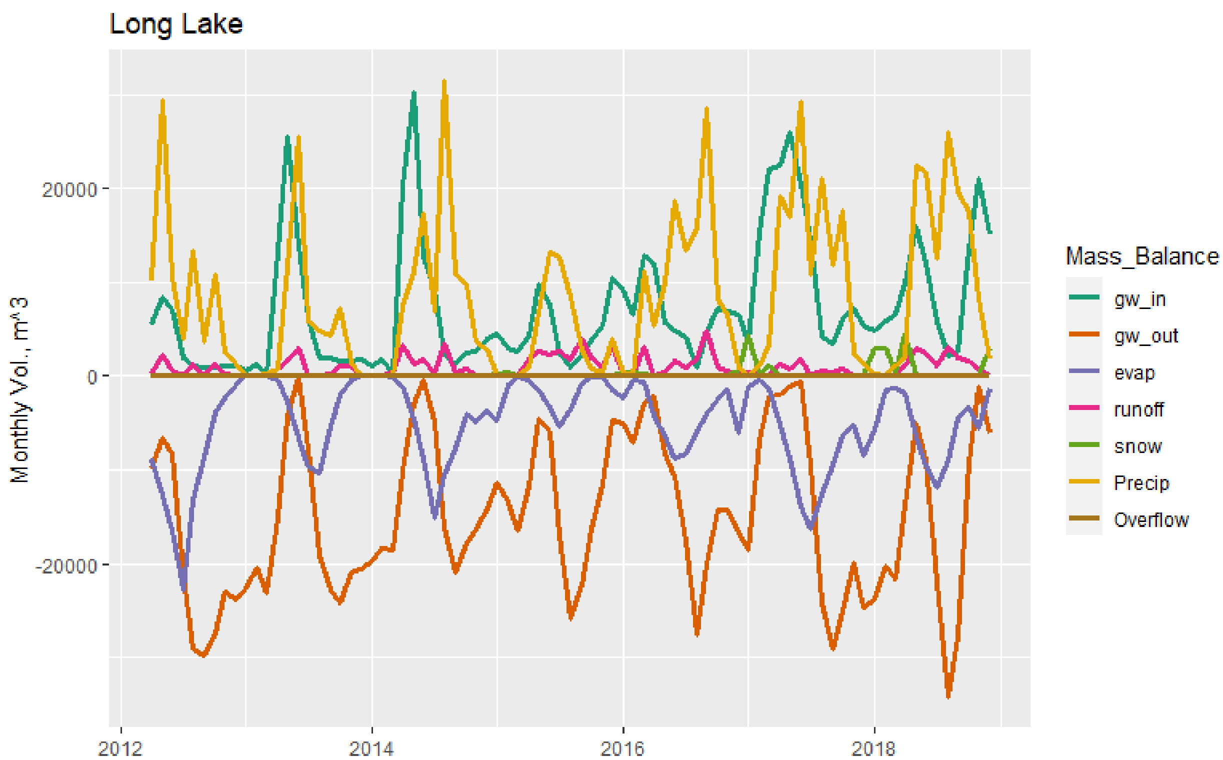

Figure 5. Modeled lake mass balance for Long Lake**.**

Modeled thermal profiles for Long Lake show that the lake does not stratify, and generally matches the measured temperature profile data (Figure 6).

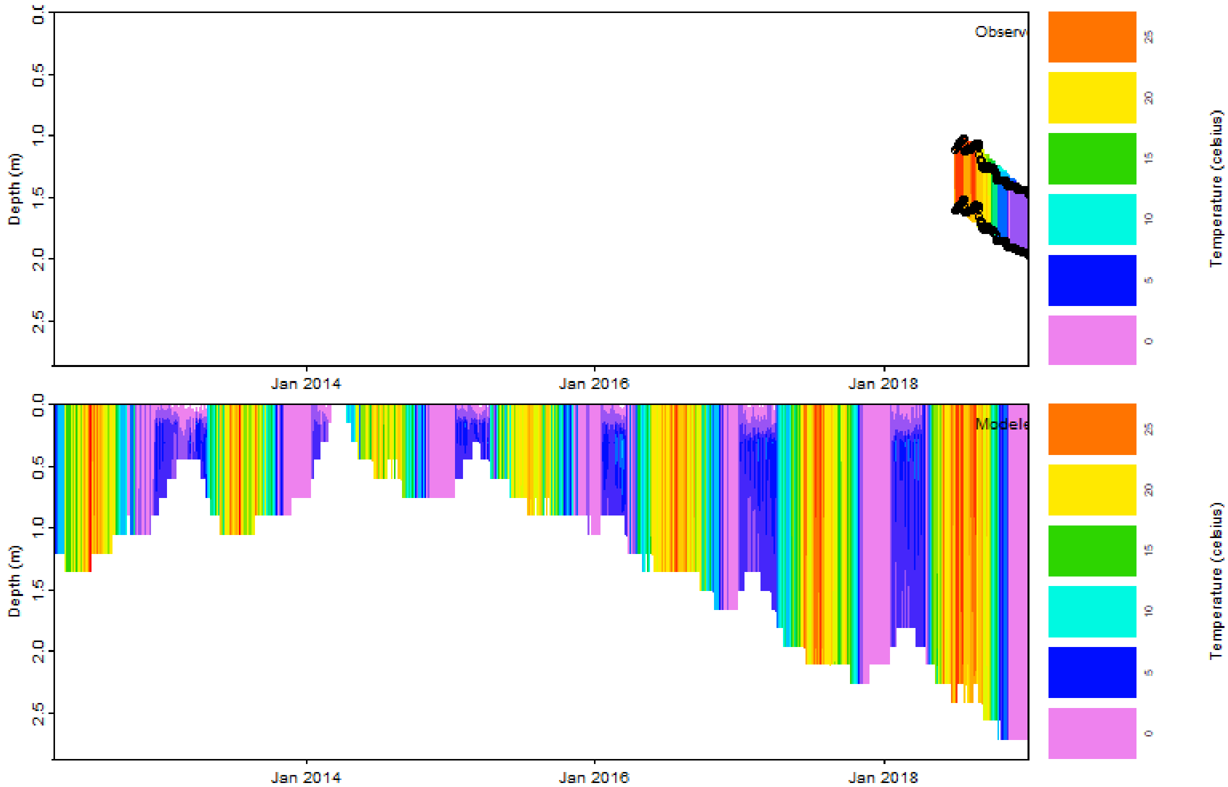

Figure 6. Modeled (lower panel) and measured (upper panel) lake stage thermal stratification for Long Lake**.** Black dots on the upper panel are observations points.

Plainfield Lake

Like Long Lake, Plainfield Lake needed no adjustment to groundwater inflow or outflow. Modeled stage values reasonably match the measured stage values, although the only stage data available for Plainfield Lake is in the last year of the study period (Figure 7), with an RMSE of 0.2 meters.

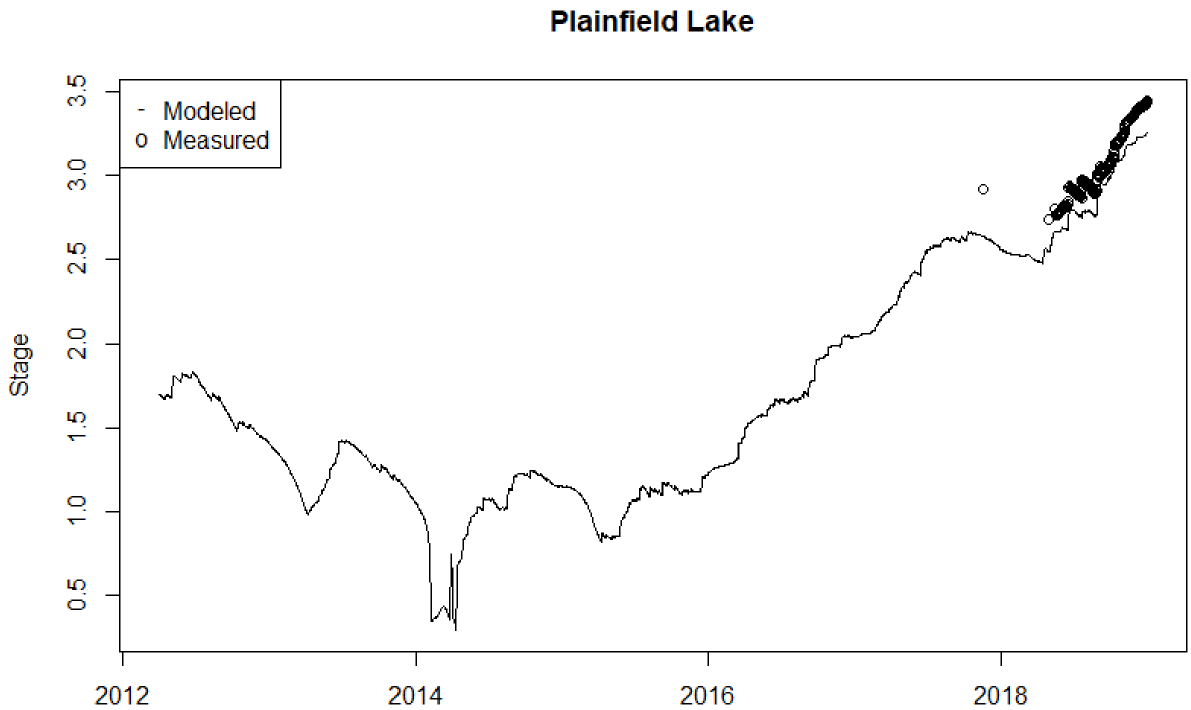

Figure 7. Modeled and measured lake stage values, in meters, for Plainfield Lake**.**

The modeled mass balance for Plainfield Lake shows precipitation and groundwater inflow are similar in magnitude, and groundwater outflow and lake evaporation are similar in magnitude as well (Figure 8).

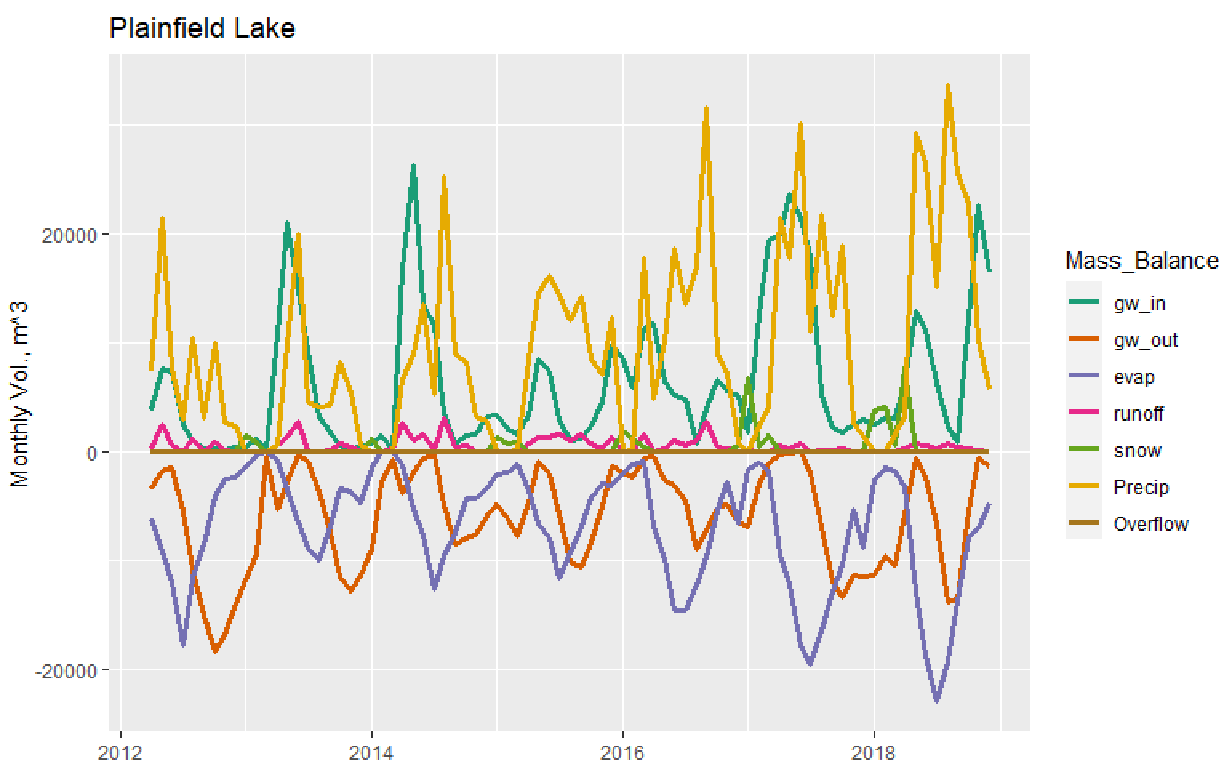

Figure 8. Modeled lake mass balance for Plainfield Lake.

Modeled thermal profiles for Plainfield Lake show the lake does not stratify, and generally matches lake temperature profiles (Figure 9).

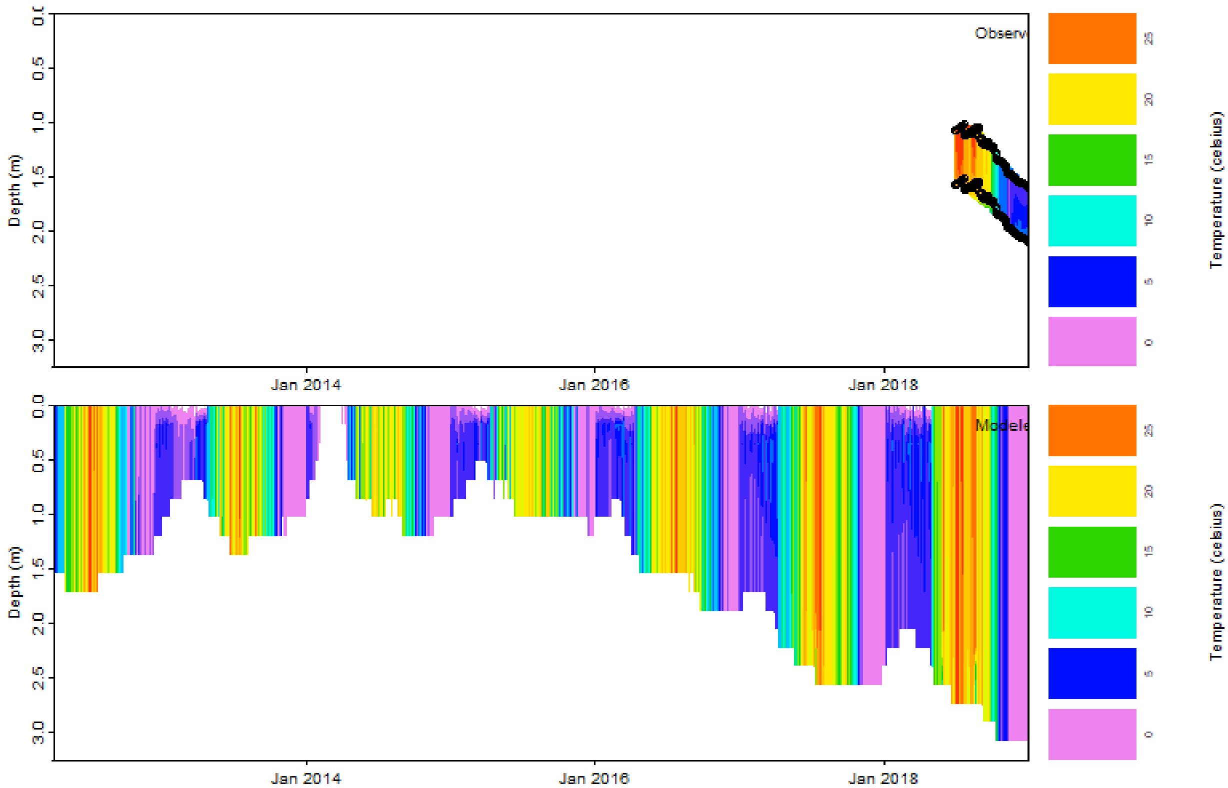

Figure 9 Modeled (lower panel) and measured (upper panel) lake stage thermal stratification for Plainfield Lake**.** Black dots on the upper panel are observations points.

Lake Evaporation Estimations

The modeled lake evaporation from GLM was averaged on a monthly timestep for each lake and compared to the Hamon equation for monthly lake evaporation rates (Figure 10). Both the Hamon and GLM lake evaporation estimates show the same general trend of peak evaporation rates during the summer and minimum evaporation rates during the winter, but the Hamon equation tends to overpredict summer peak rates and underpredict winter minimums, as compared to the GLM lake evaporation estimate. To compensate for the differential, the Hamon lake evaporation estimation was regressed by 25% towards the long-term mean evaporation rate for each lake (Figure 10). The corrected Hamon lake evaporation estimator was used as an input for the Lake Package in MODFLOW for the history-matching period (2012-2018), and for the additional modeling scenarios over a longer 38-year timeframe (Fienen et al, 2021).

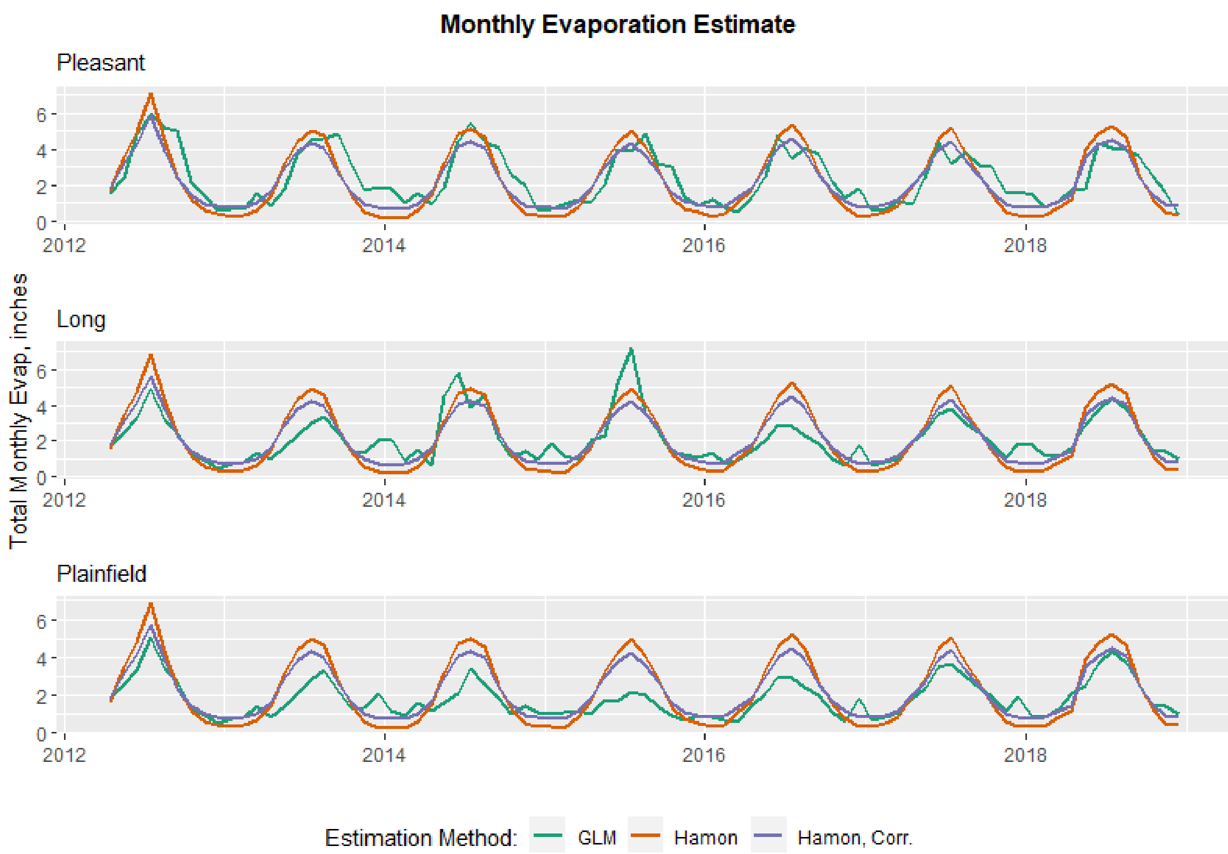

Figure 10. Monthly lake evaporation rate estimates for the three study lakes using GLM, Hamon, and Corrected Hamon methods.

Limitations

As with any modeling effort, the approaches presented here have necessary assumptions about physical processes and limitations based on how the models are used. The data collected to verify the GLM results was only collected for a short period in 2018, a period of very high water levels. Additional temperature profile information, particularly during lower water periods, could serve to further refine the GLM parameterization to better reflect thermal stratification within the lakes over a range of lake level regimes. Other types of data, such as ice-on and ice-off dates would also help constrain model efficacy. The Hamon equation does not produce a perfect match to the GLM estimation of evaporation, even after a 25% correction. Because there was still uncertainty in the lake evaporation estimates, the MODFLOW history-matching process allowed lake evaporation rates to vary in order to better match modeling targets, but found that the lake evaporation rates did not need to be substantially adjusted from the Corrected Hamon rates (Fienen et al, 2021).

References

Hamon, W.R., 1961, Estimating potential evapotranspiration: Journal of Hydraulics Division, Proceedings of the American Society of Civil Engineers, v. 87, p. 107-120.

Leaf, A.T., and Haserodt, M.J., 2020, Hydrology of Haskell Lake and investigation of a groundwater contamination plume, Lac du Flambeau Reservation, Wisconsin: U.S. Geological Survey Scientific Investigations Report 2020-5024, 79 p., https://doi.org/10.3133/sir20205024.

Harwell, G.R., 2012, Estimation of evaporation from open water – A review of selected studies, summary of U.S. Army Corp of Engineers data collection and methods, and evaluation of two methods for estimation of evaporations from five reservoirs in Texas: U.S. Geological Survey Scientific Investigations Report 2012-5202, 96 p., https://doi.org/10.3133/sir20125202.

Hipsey, M.R., Bruce, L.C., Boon, C., Busch, B., Carey, C.C., Hamilton, D.P., Hanson, P.C., Read, J.S., de Sousa, E., Weber, M., and Winslow, L.A., 2019, A General Lake Model (GLM 3.0) for linking high-frequency sensor data from the Global Lake Ecological Observatory Network (GLEON), Geosci. Model Dev., 12, 473-523, https://doi.org/10.5194/gmd-12-473-2019.

Robertson, D.M., Juckem, P.F., Dantoin, E.D., Winslow, L.A., 2018, Effects of water level and climate on the hydrodynamics and water quality of Anvil Lake, Wisconsin, a shallow seepage lake, Lake and Reservoir Management, https://doi.org/10.1080/10402381.2017.1412374.

Voter et al., CSLS Technical Report: Lake Ecosystem Characterization and Response, April 2021.

Mitchell, K.E., Lohmann, D., Houser, P.R., Wood, E.F., Schaake, J.C., Robock, A., Cosgrove, B.A., Sheffield, J., Duan, Q., Lou, L., et al., 2004, The multi-institution North American Land Data Assimilation System (NLDAS): utilizing multiple GCIP products and partners in a continental distributed hydrological modeling system. J. Geophysical Res. 109:D07S90, https://doi.org/10.1029/2003JD003823.

Fienen et al., CSLS Technical Report: USGS Modeling Documentation, April 2021.

U.S. Geological Survey, 2016, National Water Information System data available on the World Wide Web (USGS Water Data for the Nation, accessed July 17, 2020, at https://waterdata.usgs.gov/wi/nwis/inventory/?site_no=443320089212304