A comparison of remote sensing estimates of lake evaporation with pan evaporation measurements along the Savannah River Basin

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ABSTRACT. Lake evaporation significantly affects water availability in many river basins. As water resources are strained from droughts or population and industry growth, water management plans are paramount. However, without a proper understanding and accurate estimate of lake evaporation, such plans may be subject to failure. Within this paper, two methods for estimating lake evaporation are considered. The first is a satellite-based method where mass transfer models (three are investigated) that incorporate high resolution satellite measurements of water surface temperature from the MODIS sensor. The second method is the traditional pan method using monthly derived pan coefficients. These models are used to estimate the historical lake evaporation within the five major lakes encompassing the Savannah River Basin. This comparative study clearly reveals differences between the two methods on a daily, monthly, and yearly time scale. Results show significant variation in the seasonal evaporation trends between the mass transfer method and the pan method. There are also differences in the seasonal evaporation variation from lake to lake.

INTRODUCTION

Evaporation from lakes and reservoirs is an important component of the water cycle. Accurate measurement of evaporation is becoming increasingly important as population and economic growth stress water resources. This in turn requires evaporation estimates to be accurate over smaller time scales. Accurate monthly evaporation estimates will become increasingly important during periods of drought. The goal of this paper is to examine seasonal variation in evaporation using pan and mass transfer estimates of evaporation for the lakes of the Savannah River Basin (SRB)

There are many approaches to estimating evaporation from lakes including mass balance, energy balance, mass transfer calculations, and pan measurements. Each method has distinct advantages and disadvantages.

The mass balance method equates the change in volume of water within the lake with the difference between the volume inflow and outflow (Patra 2001). Inflows include stream flows and direct rainfall. Outflows include river outflow (possibly controlled by a dam) and evaporation. The main advantage of this method is that it involves very simple calculations. However, the accuracy of the evaporation estimate is controlled by the accuracy of the measurements of each of the inflows and outflows. Unfortunately, some of the inflows and outflows can be hard to quantify, particularly water exchange between the lake and groundwater.

The energy balance method balances the net incoming radiant energy at the lake surface with heat transfer into the lake, the sensible heat loss to the atmosphere and the latent heat loss due to evaporation (Linsley et al. 1982). Again, the accuracy of the calculation depends on the accuracy of the parameterizations of each of these energy fluxes, as well as the accuracy of the measurements which support them.

Mass transfer methods parameterize the evaporation rate in terms of the surface to bulk air humidity difference and a mass transfer coefficient which is typically parameterized as a function of wind speed (Gupta 2001). As will be shown below, this approach requires measurements of only air temperature, wind speed, humidity, and water surface temperature. These have been easily obtained from standard meteorological stations, with the exception of water surface temperature. However, the recent launch of the Aqua and Terra satellites with the MODIS sensor has made available measurements of lake surface temperature on a 1 km grid four times per day.

The most common method for estimating lake evaporation is the pan method (Linsley et al. 1982). In this method the evaporation rate is measured directly from a Class A evaporation pan and then a correction is

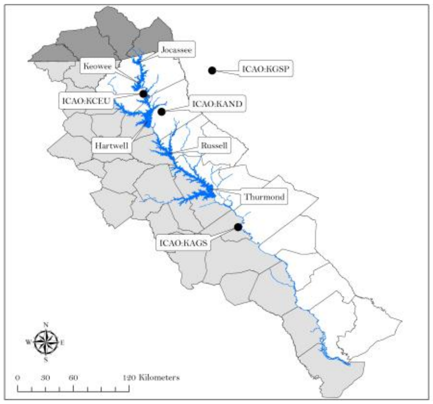


Figure 1: Map showing the major lakes of the Savannah River basin and the ASOS stations used for collecting weather data.

applied, through a pan coefficient, to account for the difference between the pan and free water surface (FWS) evaporation. The pan method is simple, and is a direct estimate of evaporation near the lake. However, the pan method suffers from the fact that the pan thermal behavior can be significantly different from that of the lake, and the meteorological conditions on the shore where the pan is located can be different from those over the lake.

MODEL

This study presents a comparison between pan evaporation estimates and calculated evaporation using three different mass transfer parameterizations. The goal of the study is to investigate seasonal variation in evaporation rates for the five major lakes along the Savannah River basin (SRB). See figure 1.

The three mass transfer parameterizations used all have the same basic formulation

$$(m'') = h_m (q_s^* - q_a)$$

where m'' is the evaporation rate, h_m is a mass transfer coefficient, and q_s^* and q_a are the specific humidity at the surface and in the ambient air, respectively. The three parameterizations used are based on turbulent boundary layer models (designated by TBL), heat transfer parameterizations (HT), and a generalized aerodynamic model (AERO). All three models have been used for parameterizing lake evaporation (Brutsaert 1982, Dalton 1802, Gupta 2001, Sartori 2000, and Sweers 1976). The only difference between the models is how the mass transfer coefficient is parameterized in terms of the material properties and local weather conditions.

Local weather conditions were obtained from the National Weather Service ASOS database. The weather stations used in the study are shown in figure 1. Lake surface temperatures were obtained from the MODIS sensor on the Terra and Aqua satellites. Measurements are made four times a day with data for cloudy days automatically excluded from the data base. Missing data were filled using the HANTS algorithm (Julien et al. 2006). The lake surface temperature was combined with the local weather data to calculate the evaporation rate for each lake four times a day. These four measurements were then averaged to get a daily average evaporation rate over the entire period of record for which MODIS data is available (July 2002 to December 2012).

The daily pan evaporation rate for each of the five major lakes along the SRB was calculated using data from the Clemson Class A pan and lake specific monthly pan coefficients derived from the NOAA FWS evaporation atlas.

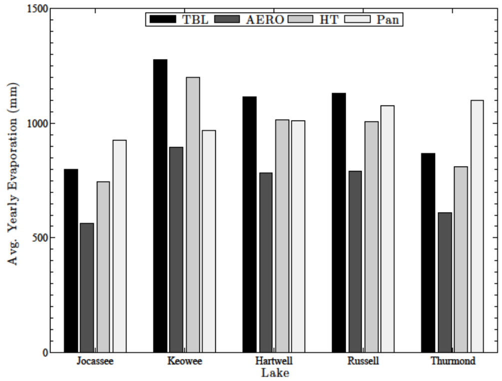


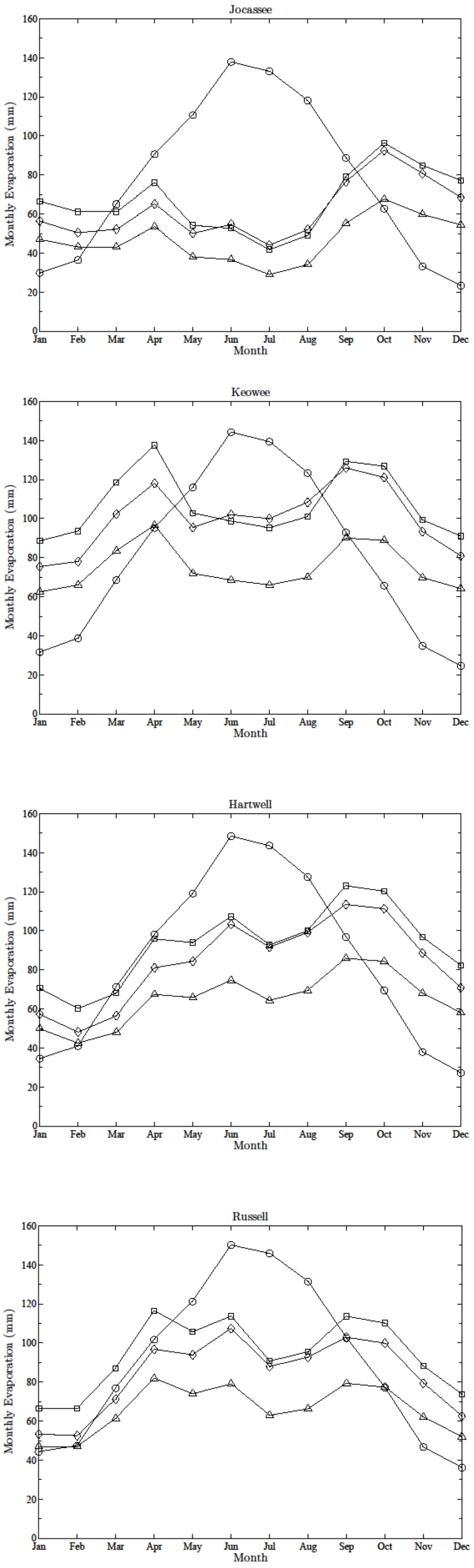
Figure 2: Predicted average annual lake evaporation for each data set and each of the major lakes along the SRB.

RESULTS

A comparison of the annual average evaporation for each lake and each model is shown in figure 2. The data indicates that there is no substantial difference between the pan evaporation data and the three mass transfer data sets on an annual basis. For three of the five lakes the pan data lies within the range of the mass transfer data sets.

The main purpose of this study is to examine seasonal variation in evaporation rates along the SRB. Plots of monthly average evaporation rate for each of the SRB lakes and each evaporation data set are shown in figure 3.

The data shows that there is a significant variation in the month-to-month evaporation between the mass transfer methods and the pan method. The pan method shows peak evaporation in the summer for all five lakes, whereas, with the exception of Lake Hartwell, the mass transfer method shows a clear double peak in evaporation with the maximum being recorded in the early fall. Lake Hartwell exhibits a single major peak in the fall. For all five lakes, there is a substantial difference



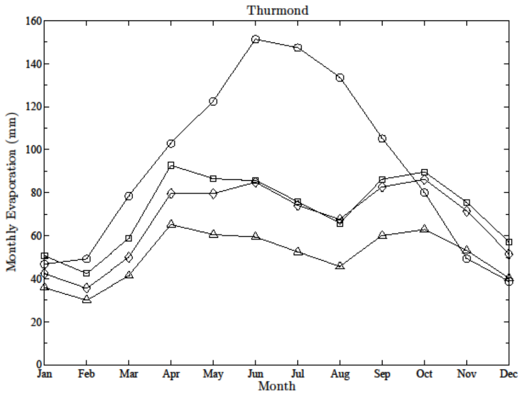


Figure 3: Plots of the monthly average evaporation for each of the five major SRB lakes and each data set - TBL (□), AERO (Δ), HT (◊), and pan (○).

in the estimated seasonal variation in evaporation between the pan and mass transfer methods.

Scatter plots of the pan data versus the mass transfer data for daily, monthly, and yearly time scales are shown for Lake Hartwell in figure 4. The AERO model was arbitrarily chosen for the mass transfer method since the seasonal trends were similar for all of these methods. The data is almost completely uncorrelated on a day-to-day basis. The level of correlation increases with an increased averaging time.

DISCUSSION

One possible explanation for the difference in seasonal patterns of lake evaporation observed in figure 3 is that the lakes have substantially larger thermal inertia than Class A evaporation pans. The water temperature in a Class A pan will vary significantly on a daily basis, whereas the time scale for heating and cooling a lake is of the order of several months. Therefore, the lake surface temperatures measured by the MODIS sensor will differ from the pan surface temperatures on a daily and monthly basis.

A further investigation of the possibility that the lake thermal inertia is responsible for the disparity between the pan and mass transfer estimates was conducted. The mean lake depth was used as a proxy for its thermal inertia. A plot of the correlation coefficient between the monthly pan and mass transfer evaporation data versus the mean lake depth is shown in figure 5. The data indicates that as the lake depth increases the pan and mass transfer evaporation data becomes less correlated.

The use of satellite measurements of lake surface temperature has the potential to significantly improve both spatial and temporal resolution in lake evaporation estimates. However, the approach presented herein still requires further refinement. For example, the weather data used was measured some distance away from the lakes rather than directly over the lake.

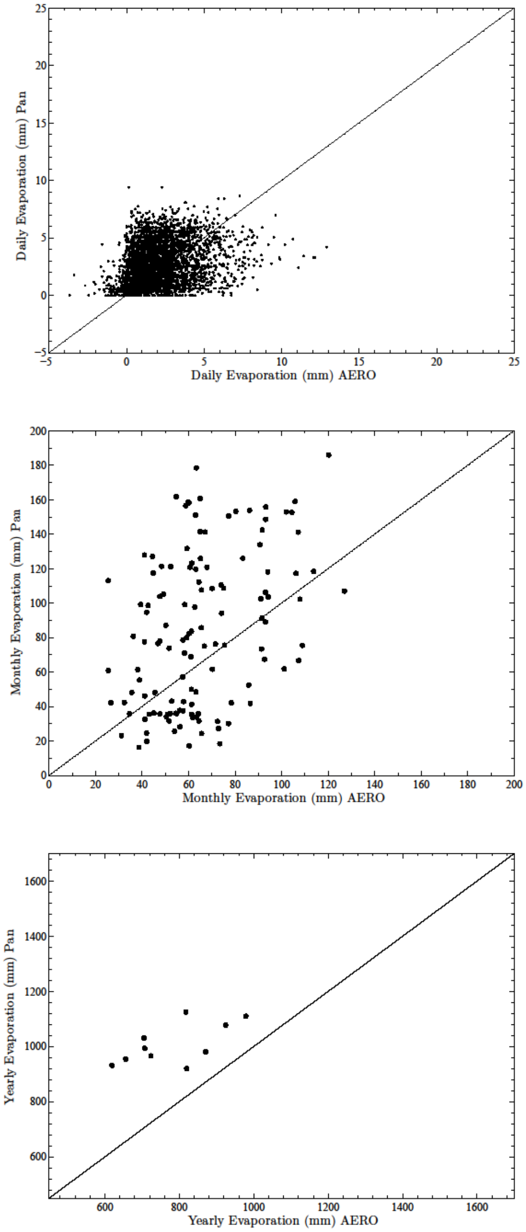


Figure 4: Scatter plot of AERO versus pan evaporation for Lake Hartwell. From top to bottom, Daily, monthly averaged, and yearly averaged. Line shows exact agreement.

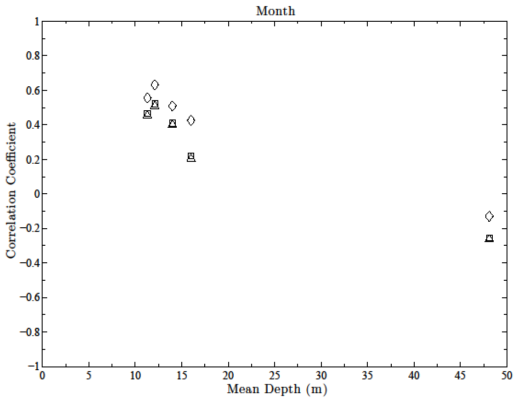


Figure 5: Plot of the correlation coefficient between the monthly mass transfer data and pan data versus mean lake depth. Symbols are the same as for figure 3.

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