APPENDIX A

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Evaporation from Large Lake Bodies

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Introduction

Evaporation losses from lakes and open surface water bodies is typically one of the largest components of the water balance (Winter and Woo 1990). However, despite the magnitude and importance of the evaporative flux term it is seldom accurately determined from an energy budget or mass transfer method due to the considerable investment in instruments and personnel. Evaporation rates were calculated only for months in which White Bear Lake (WBL) was typically ice free, April to November. Sublimation rates of blowing snow were not calculated for WBL during months typically with ice cover, December to March.

Evaporation Pan Coefficients

Evaporation pans are the most commonly used instrument to measure evaporation directly, but can differ from lake evaporation rates due to different wind and thermal regimes. One of the most popular methods used to estimate evaporation (E_0) is the product of pan coefficient (K_p) and pan evaporation (E_p) (Snyder, Orang et al. 2005).

$$E_0 = K_p \times E_p$$

A basic requirement in determining K_p is that lake evaporation is accurately known from an independent method (Winter 1981). The most commonly used coefficient to estimate lake evaporation from a Class A pan data is 0.7, but should only be applied to annual data (Kohler, Nordenson et al. 1955). Annual pan coefficients were determined from the eddy-flux measurements of evaporation made on WBL by the University of Minnesota in reference to the class A pan evaporation data from the University of Minnesota's St. Paul campus for 2015 and 2016.

Table 1. An average annual pan coefficient was determined to be 0.63, with K_p ranging from 0.59 to 0.67. The variability in annual pan coefficient was far less than the monthly variability of pan coefficients within a given year. This variability is likely why Kohler (1955) states annual lake evaporation could be estimated within 10-15% using the pan coefficient method, provided lake depth and climatic regime are considered in selecting the coefficient. Since the pan coefficients for WBL will be empirically derived from Eddy-flux evaporation observations it is expected that the annual lake evaporation could be estimated with a greater degree of certainty (within 10%) compared to simply selecting a regional K_p value. The difference between Eddy-flux annual evaporation rates and those determined from pan coefficients was 7.0% in 2015, and 3.7% in 2016. However, it is expected that evaporation rates estimated for lakes other than WBL would have a greater degree of uncertainty similar to applying a regional coefficient (10 to 15%). The large difference in pan coefficients from month to month within a given year, i.e. June 2015 was 0.41 while October 2015 was 2.66, is due to energy stored at depth within the lake and the reason other studies have suggested pan coefficients should never be used for periods of less than one year (Hounam 1973).

Table 1 Pan Coefficients (Kp) for WBL

Month	2015 WBL (mm)	2015 Pan (mm)	2015 Kp	2016 WBL (mm)	2016 Pan (mm)	2016 Kp	Average Kp
April	40	47	0.85	41	47	0.87	0.86
May	51	136	0.38	54	159	0.34	0.36
June	70	172	0.41	91	178	0.51	0.46
July	103	208	0.49	110	194	0.57	0.53
Aug	80	155	0.52	93	139	0.67	0.59
Sept	65	108	0.60	87	119	0.73	0.67
Oct	69	26	2.66	65	40	1.61	2.13
Nov	24	0	N/A	32	0	N/A	N/A
Annual	502	853	0.59	588	877	0.67	0.63

Energy Storage Coefficient

Lake evaporation is unique that it is not only influenced by climate, but also the characteristics of the lake itself such as depth and area. This introduces additional complexity through changes in water temperature and vertical mixing which influence evaporation rates. The energy budget for a lake can be written using the following equation (Lenters, Kratz et al. 2005):

$$R_{net} + Q_{sed} + A_{net} - (E + H) = S$$

Where;

R_{net} is net radiation

Q_{sed} is heat released by sediments

A_{net} is net heat advected into the lake

E is evaporation

H is sensible cooling

S is the rate of change of heat stored in the lake

To calculate monthly evaporation rates a portion of incoming solar radiation during the summer months needs to be stored within the lake and released in later months as an evaporative flux. The energy stored in the lake is the main reason why pan coefficients can be applied on a yearly basis, but not monthly as illustrated by the estimated pan coefficients for WBL. While the annual average pan coefficient was calculated to be 0.63, the average monthly coefficients ranged from 0.36 in May to 2.13 in October. To gain a better understanding of the relative portion of net radiation that would be stored in a lake the long-term energy budget at Sparkling Lake in Northern Wisconsin was studied (Lenters, Kratz et al. 2005). It revealed that on average for the 10-year study 32% of the net radiation was stored during the months of May and June. During the months of July and August the percentage of energy stored declined, while in September and October the lake was releasing energy (negative storage). **Table 2.**

Table 2 Percent of Net Radiation Stored in Sparkling Lake (1989 to 1998)
(Calculated from Table 2, Lenters, Kratz et al. 2005)

Month	Rnet (W/m2)	S (W/m2)	Stored (%)
May	148.75	47.45	32%
June	156.05	49.95	32%
July	151.3	24.85	16%
August	123.35	5.2	4%
September	71.85	-50.75	-71%
October	29.05	-68.85	-237%

Estimated Evaporation for White Bear Lake

To estimate historic monthly evaporation rates for White Bear Lake from pan evaporation data both a pan and energy storage coefficient must be used. SSPA developed the following equations to estimate monthly evaporation rates for WBL using only a pan coefficient (K_p) and a storage coefficient (K_{stor}) for the months of May through September;

$$E_t = K_p \times E_{pt}(1 - K_{stor}) + S_{t-1}(K_{stor})$$

$$S_t = K_p \times E_{pt}(K_{stor}) + S_{t-1}(1 - K_{stor})$$

E_t is the total evaporation for month t (mm)

K_p is the annual pan coefficient

E_{pt} is the total pan evaporation for month t (mm)

K_{stor} is the storage coefficient

S_t is the energy stored in the lake for month t (in mm of evaporating water)

Currently the same coefficient for storage is being used to estimate how much energy is released from storage each month, and is not being estimated with another parameter. If needed an additional parameter could be used to estimate the amount of energy that is released from lake storage each month. In April, October and November there is no storage of energy. Evaporation for each month is estimated with the following equations;

$$E_{April} = K_p \times E_{pt}$$

$$E_{Oct} = K_p \times E_{pt} + S_{t-1}(1 - K_{stor})$$

$$E_{Nov} = S_{t-1}\ ;\ Pan\ not\ measured\ in\ Nov$$

Based on the 2015/2016 empirical derived evaporations from the Eddy-fluxes for WBL (WBL) an annual pan coefficient (K_p) was estimated at 0.63 with a storage coefficient of 0.39

(K_{stor}). Pan and storage coefficients were calibrated to produce the minimal difference between the monthly observed WBL evaporation rates (WBL E) and calculated evaporation rates (Calc E) for 2015 and 2016. The monthly estimated evaporation values for 2015 and 2016 are presented in Table 3.

Table 3 2015/2016 Monthly Calculated Evaporation for White Bear Lake with Observed and Pan

Month	2015 WBL E (mm)	2015 Pan E (mm)	2015 Calc E (mm)	2015 Stored E (mm)	2016 WBL E (mm)	2016 Pan E (mm)	2016 Calc E (mm)	2016 Stored E (mm)
April	40	47	30	0	41	47	30	0
May	51	136	52	33	54	159	61	39
June	70	172	79	63	91	178	84	68
July	103	208	105	89	110	194	101	89
Aug	80	155	95	93	93	139	88	88
Sept	65	108	78	83	87	119	80	83
Oct	69	26	67	32	65	40	76	32
Nov	24	0	32	0	32	0	32	0
Annual	502	853	537		573	877	552	

Figure 1 and **Figure 2** illustrate the portion of evaporation coming from monthly solar radiation (Solar E) and the portion released from energy stored in the lake from previous months (Released E) for 2015 and 2016. There are also lines for the observed monthly pan evaporation (Pan E), observed Eddy-flux evaporation at White Bear Lake (WBL E), and the total amount of energy stored in the lake (Stored E) in each figure.

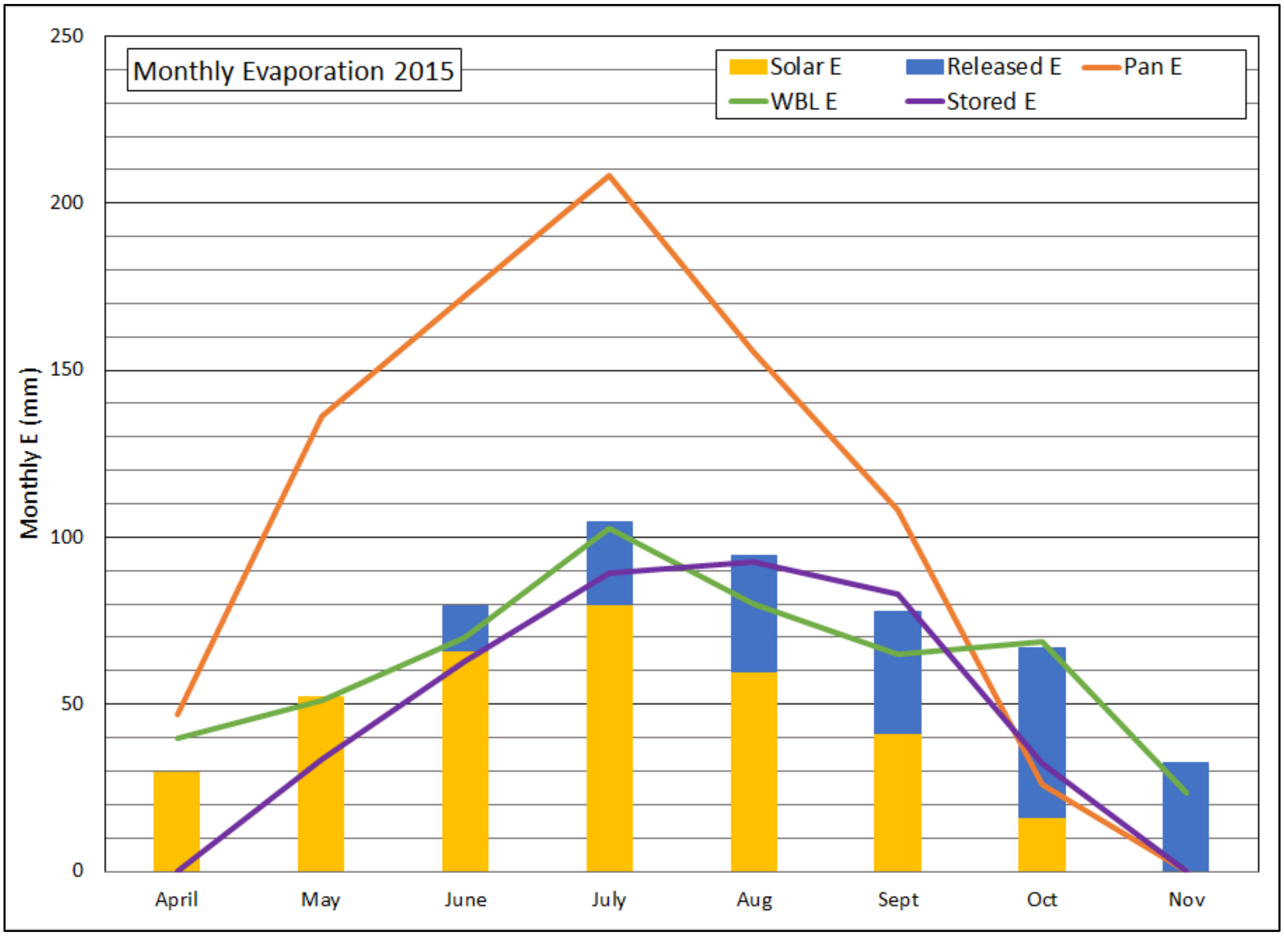

Figure 1 2015 Estimated Monthly Evaporation for WBL

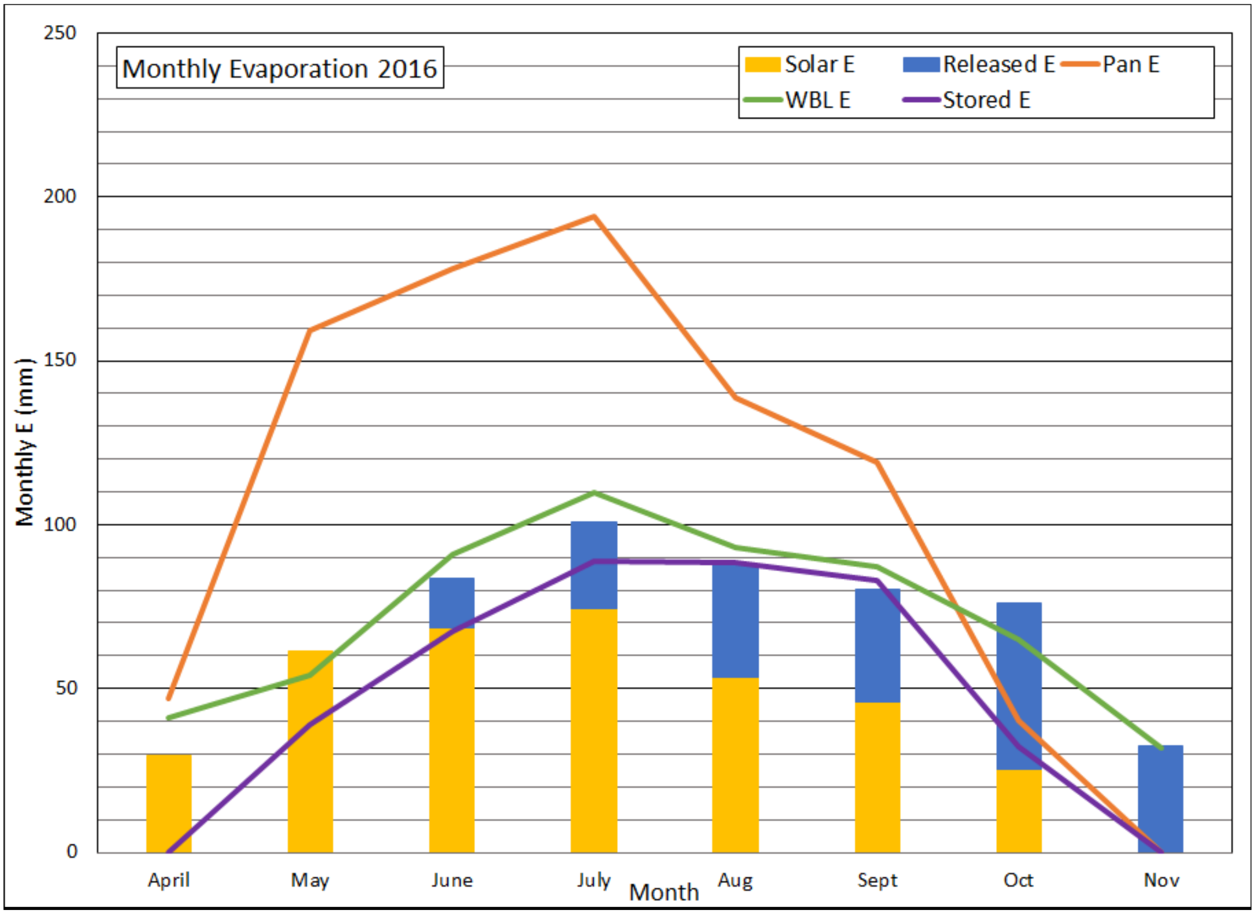

Figure 2 2016 Estimated Monthly Evaporation for White Bear Lake

The percent of energy stored each month was calculated from the estimated monthly evaporation values for WBL in 2015 and 2016 and compared to the monthly 10 year averages for Sparkling Lake in Northern Wisconsin (Table 4). The percent energy stored each month is comparable to values observed at Sparkling Lake except for September which had the largest discrepancies between the two lakes. The reason for this discrepancy is likely due to the characteristics of the lake. WBL is both larger and deeper, and it would be expected that WBL would take longer to release the energy stored compared to Sparkling Lake.

The percentage of energy stored (Stored %) in WBL was calculated using the following equation:

$$Stored\%_t = \frac{K_p \times E_{pt} - E_t}{K_p \times E_{pt}}$$

Where

$Stored\%_t$ is the percent energy stored for month t (%)

E_t is the calculated total evaporation for month t (Calc E, mm)

K_p is the annual pan coefficient (0.63)

E_{pt} is the total pan evaporation for month t (Pan E, mm)

Table 4 Comparison Percent Energy Stored between Sparkling Lake and White Bear Lake

Month	Stored % Sparkling Lake	Stored % WBL 2015	Stored % WBL 2016	Difference
May	32%	39%	39%	7%
June	32%	27%	25%	-6%
July	16%	20%	17%	3%
Aug	4%	3%	-1%	-3%
Sept	-71%	-14%	-7%	61%
Oct	-237%	-311%	-199%	-18%

Validation to Williams Lake Minnesota

Evaporation rates calculated for WBL were validated using 5 year monthly averages for Williams Lake in Northern Minnesota for 1982 to 1986 (Sturrock, Winter et al. 1992). Evaporation rates were calculated for Williams Lake using both the energy budget and the mass transfer methods. Figure 3 illustrates the pan storage coefficient model developed for WBL can reasonably estimate evaporation rates for lakes in the region historically. Differences between observed and estimated evaporation are expected since Williams Lake is much smaller in area and shallower in depth and located 180 miles from WBL. A new pan and storage coefficient could be determined for Williams Lake to provide better estimates of evaporation, especially in later months; however, the data required for this process is not available for any of the other lakes within the model domain. It is however possible that the pan and storage coefficient may be adjusted for an individual lake from the values determined for WBL during the calibration process.

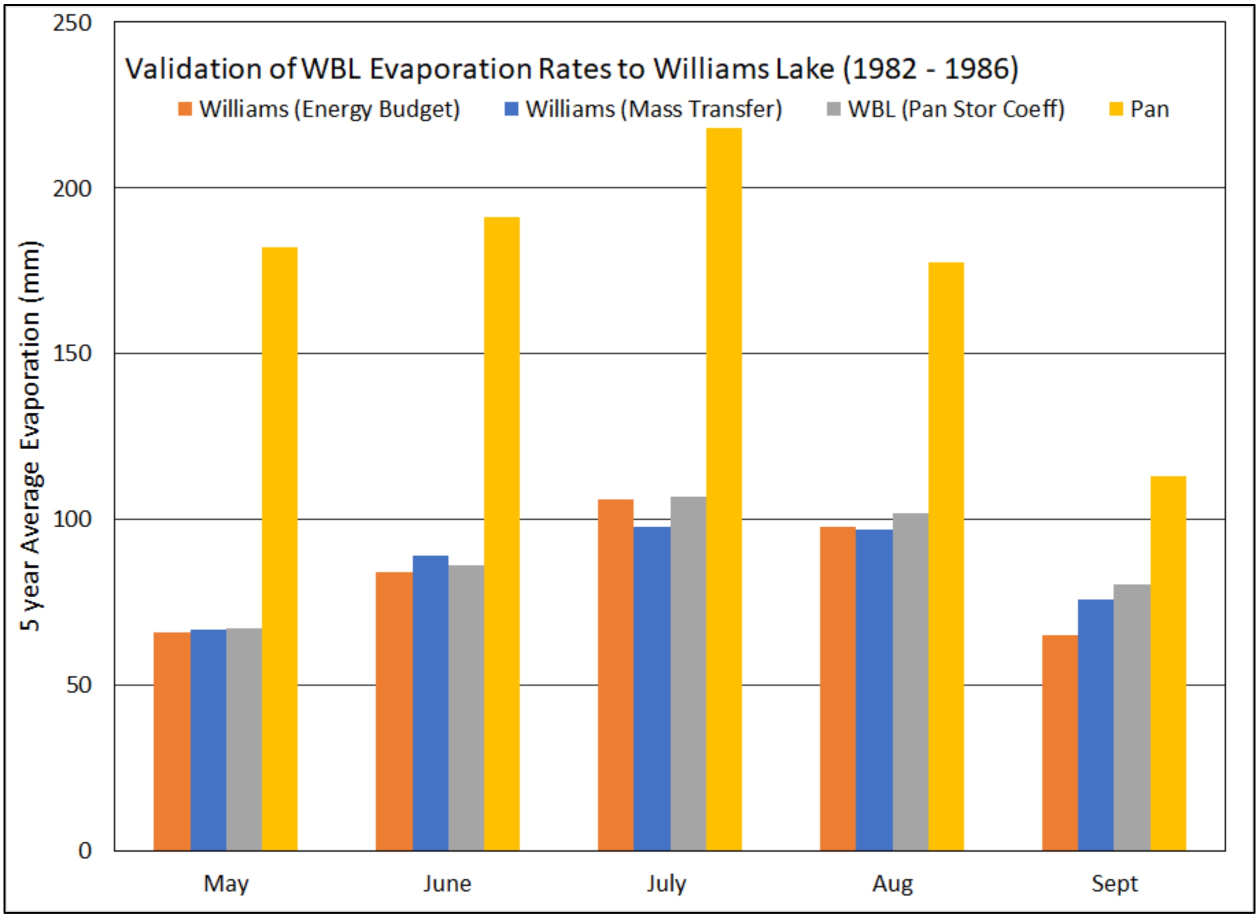

Figure 3 Validation of WBL Estimated Evaporation to Williams Lake (Sturrock, Winter et al. 1992)

Conclusion

Evaporation estimated from pan evaporation using both a pan and storage coefficient provide reasonable monthly rates that can be incorporated into model simulations. Validation to Williams lake, MN demonstrates that empirically derived lake evaporation model can be applied both historically and to lakes within the region without substantial errors. Therefore, pan and storage coefficients developed for WBL could also be applied to other lakes of interest within the model domain. Winter sublimation rates of blowing snow were not calculated as it is dependent on snow depth, density and wind speed and difficult to determine. Sublimation losses could account for significant snow pack losses before snowmelt occurs and should not be assumed negligible.

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