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Mr. Patrick Sweetland, Director
Dept. of Water and Wastewater Resources
City of Daly City
153 Lake Merced Blvd.
Daly City, CA 94015

Subject: Estimating and Measuring Evaporation from Lake Merced

Dear Mr. Sweetland:

The San Francisco Public Utilities Commission (SFPUC) is presently adding municipal (Hetch-Hetchy) water to Lake Merced in a controlled experiment to refine prior estimates of lake seepage rates. At a planning meeting at SFPUC on July 8, 2003, the question of errors associated with estimating evaporation rates during the test was raised. I offered to investigate the feasibility of monitoring lake evaporation during the test. Although seemingly a simple task, the California Department of Water Resources states in the introduction to Bulletin 73-79, Evaporation from Water Surfaces in California, that "lake evaporation is exceedingly difficult to measure directly." Before initiating a new monitoring effort, it seemed prudent to consider whether new data would likely improve on prior estimates and measurements of evaporation.

Accurate evaporation data will be needed on an ongoing basis for management of Lake Merced, particularly if the fate of water added to the lake is to be tracked as part of a conjunctive use program or to determine the cost-effectiveness of measures to maintain lake levels. To put the importance of evaporation in context, it is worth noting that all water budgets that have ever been constructed for Lake Merced list evaporation as the single largest outflow, ranging from about 58 to 85 percent of total outflow.

The data evaluated in this letter report lead to the conclusion that uncertainty in evaporation estimates contributes substantial uncertainty to estimated seepage rates. The report recommends that an evaporation monitoring program be implemented with a minimum duration of one year. The remaining sections of the report provide detailed evaluation of several previous and new estimates of average monthly lake evaporation and the feasibility of estimating deviations from average evaporation based on meteorological data from nearby weather stations. A final section discusses instrumentation, logistical and accuracy issues associated with establishing a new evaporation monitoring program.

Measurement and Estimation of Evaporation

Evaporation from water surfaces is usually measured by one of two methods: an evaporation pan or a weather station. Both methods are subject to significant uncertainty. In the case of pan evaporation, the uncertainty stems from the large but usually unknown difference between evaporation from a standard Class A pan (4 feet in diameter) and evaporation from a much larger nearby water body, with pan evaporation always exceeding lake evaporation. The "pan coefficient" is the ratio of the two evaporation rates and is multiplied by pan evaporation to estimate lake evaporation. Pan coefficients are quite variable depending on relative humdity, the environment surrounding the pan and lake, and the location of the pan with respect to the lake and prevailing wind direction. In the few situations where it has been possible to measure lake evaporation by other means, pan coefficients have been found to range from 0.6 to 0.9. Relatively low coefficients are common in arid areas and high coefficients are common in humid areas. Although efforts can be made to minimize differences between pan and lake evaporation, there is no way to quantify the effects of those steps on the pan-to-lake coefficient. For example, floating pans and screened pans can achieve pan-to-lake coefficients greater than 0.9 under some circumstances (Blaney and Corey, 1955). Thus, estimation of lake evaporation from pan evaporation is subject to an uncertainty on the order of +/-10% under most conditions.

Weather stations do not measure evaporation directly but estimate it indirectly using an energy balance equation that includes energy consumed by evaporation of water. The stations measure solar radiation, relative humidity, air and water temperature, and wind speed. These are the key variables in the Penman and Penman combination equations typically used for calculating evaporation. The variables are supposed to be measured at a height of 2 meters above a large expanse of the evaporating surface. To accurately measure lake evaporation, the instrument platform would need to be in the lake at a location with a large upwind fetch of lake surface and would need to rise and fall with seasonal fluctuations in lake levels. Deviations from these conditions introduce unknown uncetainties in the accuracy of the evporation estimate. Measurement errors for each of the sensors contribute addtional uncertainty to the estimate.

An alternative and convenient potential source of evaporation estimates for Lake Merced are the weather stations operated in numerous locations throughout the state by the California Irrigation Management and Information System (CIMIS). These stations measure the aforementioned set of variables needed to estimate evaporative demand on an hourly basis, and current and historical data are available on-line. The stations report evaporative demand as reference evapotranspiration (ET_0) rather than open-water evaporation. ET_0 is the amount of water evaporated from a large expanse of well-watered grass. The ET_0 data can be converted to evaporation estimates by first converting to pan evaporation using a monthly pan-to-crop coefficient, and then converting to lake evaporation using the pan-to-lake coefficient. Obviously, each of these coefficients is subject to considerable error for a given location. Furthermore, CIMIS stations are located primarily in agricultural areas, and there are very few within the coastal fog belt. No CIMIS station is located near the coastline within 50 miles of Lake Merced.

Evaporation and ET_0 are correlated with each of the four climate variables in the Penman equation, but the correlation with any one or two of them is often poor. This is illustrated by the scatterplots in Figure 1, which relate monthly ET_0 and monthly average temperature during 1983-2002 at the Castroville CIMIS station for the months of July through September. The graphs suggest there is some correlation between the two variables, but the r-squared values are low (0.03-0.39). Thus, partial climate data, such as air temperature data from the Richmond-Sunset weather station near the west end of Golden Gate Park might not be sufficient to estimate evaporation or deviations from average evaporation at Lake Merced.

The coastal fog gradient introduces substantial uncertainty into any estimate of Lake Merced evaporation based on pans or weather stations located elsewhere. Evaporative demand at the coastline is only 65% as large as evaporative demand at weather stations 12-20 miles inland (California Department of Water Resources 1975). The presence of coastal ridges such as the central highlands of San Francisco can further accentuate the difference between climate at the coast and climate just a few miles inland. For this reason, weather data from San Francisco International Airport would not likely produce accurate estimates of evaporative demand at Lake Merced, although the magnitude of the error is unknown.

Estimates of Average Monthly Evaporation

Several estimates of average monthly evaporation from Lake Merced can be evaluated with respect to the above sources of uncertainty. The U. S. Geological Survey study of Lake Merced presented local and regional pan evaporation data along with estimated lake evaporation and tule evapotranspiration (Yates et al. 1990, p. 31) . A standard Class A evaporation pan was deployed for that study on a raft floating in a cove amongst tules near the north end of South Lake from May through September of 1988. The data are plotted in Figure 2. The USGS report compared these values with estimates of average monthly evaporative demand (pan evaporation) for coastal zones (DWR 1975), which are also shown in the figure. The coastal zone estimates are an average of values for the northern and central California coast areas, but the source does not indicate what the values represent with respect to the coastal fog gradient. They probably represent an average for evaporation pans located near the coast, and most of the pan stations were probably located farther inland than Lake Merced. This would explain why the DWR curve is higher than measured pan evaporation at Lake Merced.

The USGS report estimated Lake Merced evaporation during 1988 using a two-step procedure, but no estimate of the uncertainty was indicated. First, the measured pan evaporation during May-September was extended to Ocotber-April by adjusting the DWR estimates of average monthly coastal evaporation so that the ratio of local to regional evaporation was the same as during May-September. Then the monthly pan evaporation was multiplied by a pan-to-lake coefficient of 0.75. No data was presented to support the selection of the coefficient, except to note that the coefficient is commonly higher than the typical value of 0.70 in humid environments. The USGS estimates of Lake Merced evaporation are also shown in Figure 2.

There are several large sources of uncertainty in the USGS estimates that limit their usefulness for estimating current evaporation. First, the pan data for May-September are for 1988 specifically, while the estimates for October-April represent long-term averages. The irregularity of the monthly values during May-September suggest that deviations from average conditions during 1988 were on the order of 0.5-0.8 inches, or 10-20%. Second, the pan-to-lake coefficient could easily be too low by 10-15%. Relative humidity close to the coast turns out to be consistently quite high, averaging 87%. This could support the selection of a pan-to-lake coefficient of 0.85 or 0.90, particularly given the location of the pan on a raft close to the lake surface. Adding these uncertainty values results in an uncertainty in lake evaporation of 20-35%, which is equivalent to as much as 0.3 inches per month (in/mo) in winter and 1.5 in/mo in summer.

Another estimate of Lake Merced evaporation can be obtained from the CIMIS station in Castroville. This station is located about 3 miles from the coast in the Salinas Valley, where fog effects extend a large distance inland. Of all the CIMIS stations, its climate is probably the most similar to the climate at Lake Merced. The advantages of using the Castroville data for estimating evaporative demand are that the period of record is long enough to provide a statistically based estimate of evaporation variability and that current data are available via the internet – which could be convenient for ongoing lake management purposes. Average monthly ET_0 at Castroville during 1983-2002 is shown as the red curve in Figure 3, with error bars extending to plus-or-minus one standard deviation. The error bars range from 0.25 inches in winter months to 0.8 inches in summer months. Estimates of lake evaporation based on the ET_0 data are represented by the blue curve in Figure 3. Published pan-to-crop coefficients for California's Central Valley range from 0.71 in December to 0.78 during April-September (DWR 1979). Dividing the ET_0 values by these coefficients yields estimates of monthly pan evaporation at Castroville. Multiplying these estimates by a constant pan-to-lake coefficient of 0.85 (based on high relative humidity) results in the lake evaporation estimates shown in the figure. These estimates are considerably higher than the estimated lake evaporation estimates developed by the USGS (Figure 2). The difference ranges from 0.99 inches (122% of the USGS value) in January to 2.16 inches (92% of the USGS value) in April. Obviously, the discrepancy between the estimated averages is very large. However, the standard deviations of monthly ET_0 as a percent of average are probably accurate indications of the variability from year to year in monthly Lake Merced evaporation.

Comparison of Evaporation Magnitude and Uncertainty with Lake Seepage Rates

Average monthly evaporation, annual variation in evaporation, and uncertainty in evaporation are all large compared to estimated seepage rates from Lake Merced. Consequently, the seepage rate estimates -- which are calculated as the residual in a water balance that includes estimated evaporation -- are themselves subject to considerable uncertainty. For example, an analysis of the closely-monitored addition of 345 ac-ft of water to the lake in October 2002 concluded that the seepage rate was 0.70 in/mo before the addition and 2.10 in/mo after the addition (Luhdorff & Scalmanini Consulting Engineers 2003). Lake evaporation during the test was estimated to equal 1.97 in/mo, or as large or larger than the seepage rate. The evaporation rate was the estimated long-term average evaporation lake based on DWR coastal zone pan data presented in the USGS report, and lake area (including tules) was assumed to equal 175.1 acres.

The error in estimating evaporation for October 2002 is the sum of the error in estimating long-term average evaporation for October and the error in estimating the deviation of actual evaporation during October 2002 from average evaporation. The preceding section indicated that uncertainty in the pan-to-lake coefficient alone could contribute an error of 10-15%, or about 0.2-0.3 in/mo in average evaporation for October. The standard deviation of annual variations in October evaporation (from the error bars in Figure 3) is approximately 0.43 inches. Assuming a normal distribution, there is a 69% probability that evaporation during October 2002 was within 0.43 inches of the long-term average. For a confidence level of 95%, the uncertainty increases to 0.86 inches. Total uncertainty for the 95% confidence level is on the order of 1.06-1.16 in/mo, or about 56% of the evaporation rate and 53-159% of the estimated seepage rates (after and before the water addition, respectively). Obviously, uncertainty in estimating evaporation results in a large uncertainty in estimating seepage.

To cast the evaporation uncertainty in water-resources terms, it can be expressed as an equivalent flow in million gallons per day, given a lake area of 175.1 acres (the October 2002 area). The approximate uncertainty for October 2002 (1.11 in/mo) is equivalent to a flow of 0.17 mgd.

Evaporation errors are even more pronounced in summer, when evaporation rates are higher than in October. In contrast, the seepage rate is a function primarily of lake area, and the per-acre seepage rate does not vary appreciably by season. Assuming a July evaporation rate of 4.2 inches (DWR coastal pan evaporation x 0.75 pan-to-lake coefficient), the combined uncertainty from interannual variations (18%) and the pan-to-lake coefficient (10-15%) is 1.2-1.4 in/mo, or 61-186% of the estimated seepage rates before and after the October 2002 water addition. This translates to an equivalent seepage flow uncertainty of 0.18-0.21 mgd.

Logistical and Instrumentation Issues for Measuring Evaporation at Lake Merced

Operation of a carefully installed and maintained evaporation pan or weather station at Lake Merced could provide more accurate estimates of current lake evaporation, perhaps within 10% of the true evaporation rate. The station would need to be operated for five or more years to obtain good estimates of long-term average evaporation. Reliable correlation of lake evaporation with weather data at a nearby weather station might also require several years of concurrent operation of the two stations, and the correlations might still be poor if the reference station is not similarly situated with respect to the coastal fog gradient.

A successful evaporation monitoring program would have to address the following issues, which are discussed in detail below:

- Minimizing differences between the instruments and the lake
  - Instrument location
  - Tracking lake levels
- Distrubance by birds
- Disturbance by vandals
- Agency commitment to data program

The most accurate instrument would probably be a floating evaporation pan, but there are no standard designs for such pans and they are susceptible to wave overwash. A Class A pan on a raft would experience some differences in water temperature and light reflectance compared to lake water, and the raft itself would affect the thermal environment of the pan. A Class A pan located onshore would experience further differences related to shading by trees, wind reduction by shrubs, and ground temperatures significantly different than lake temperatures. All of these considerations also apply to weather stations. The ideal location for either type of station would be in or directly above the lake surface, followed by a station on a raft and a station onshore.

The instruments should be located toward the downwind end of the lake with respect to the prevailing wind direction, which is from the west. Because the relative humidity of the air crossing the lake is largely controlled by the nearby and upwind Pacific Ocean, errors associated with fetch length and wind orientation are probably smaller at Lake Merced than at inland lakes.

Any instruments in or on the lake would need to be able to rise and fall with changes in lake level. The cage or tether for a floating pan would need to accomodate such changes in lake level. The height of pole-mounted weather instruments would need to be adjusted each time the data logger is downloaded.

The numerous birds at Lake Merced will eagerly perch on any horizontal object near lake level, including the rim of an evaporation pan, a rain gage bucket, a radiometer or an anemometer. A coarse wire enclosure could prevent bird access to a floating pan, and strategically-placed strands of barbed wire around weather instruments could similarly deter perching.

Theft or vandalism of instruments is likely in any area accessible to the public. An offshore installation serviced by boat would probably avoid these problems, as well as provide the highest-quality data.

The most accurate and useful evaporation monitoring program would last considerably longer than the duration of the July-October 2003 water addition test and would require a moderate-to-long-term commitment by an agency or local resource stewardship group to operate the equipment and compile the data. One or two months of evaporation measurements during the water addition test would decrease the uncertainty of the lake seepage estimate for the test but would be of limited value for ongoing lake management or for estimating seepage under a wider range of hydrologic conditions. Also, the test is halfway completed as of the date of this letter, and even rapid installation of equipment would capture only a small part of the test period. A full year of data would improve the estimate of evaporation because seasonal variations that do not affect seepage could be discerned. A year of data would also be useful for correlating lake evaporation with measured ET_0 at the Castroville CIMIS station, which could allow lake evaporation during the water addition test to be retroactively estimated. Multiple years of data would provide reasonable estimates of long-term averages and correlations with other nearby weather stations. An ongoing monitoring program would be useful for management of water quality and water resources, such as by improving estimates of the residence time of lake water or estimating the amount of groundwater recharge achieved by adding water (e.g. stormwater) to the lake.

My recommendation for instrumentation is an offshore installation that combines a floating evaporation pan and a weather station. Concurrent monitoring with both sets of instruments would overcome some of their respective limitations and provide a cross-check on evaporation estimates. The installation would consist of four steel pipes driven into the lakebed in a square pattern approximately 2 feet by 2 feet and protruding 2 meters above the lake level (with telescoping extensions to accommodate changes in lake level. A floating evaporation pan would sit within the area bounded by the pipes, and a floating donut-shaped breakwater device would surround the pipes. The pipes would be enclosed by a cylinder of coarse wire mesh to prevent bird access to the pan. A standard weather station instrumentation package and data logger would be mounted on the top of the pole structure. The station would be serviced monthly (more often in summer) using a canoe or other small boat stored at the pump station. Equipment costs would be on the order of $2,300, excluding the boat. I could provide design details and/or a proposal to install and operate the station for a year if you are interested in pursuing the idea.

I hope this discussion proves useful to all of the parties actively engaged in planning and management of Lake Merced and Westside Basin groundwater resources. I have taken the liberty of sending copies to several individuals who have expressed interest in the matter and encourage you to forward it to others who might be interested. Please do not hesitate to call if you have any questions.

Sincerely,

Gus Yates

Gus Yates, RG, CHG
Hydrologist

cc. John Fio, HydroFocus, Inc.
Dave Van Brocklin, Luhdorff & Scalmanini Consulting Engineers
Greg Bartow, SFPUC
John Plummer, Friends of Lake Merced
David Dawdy, Hydrologist

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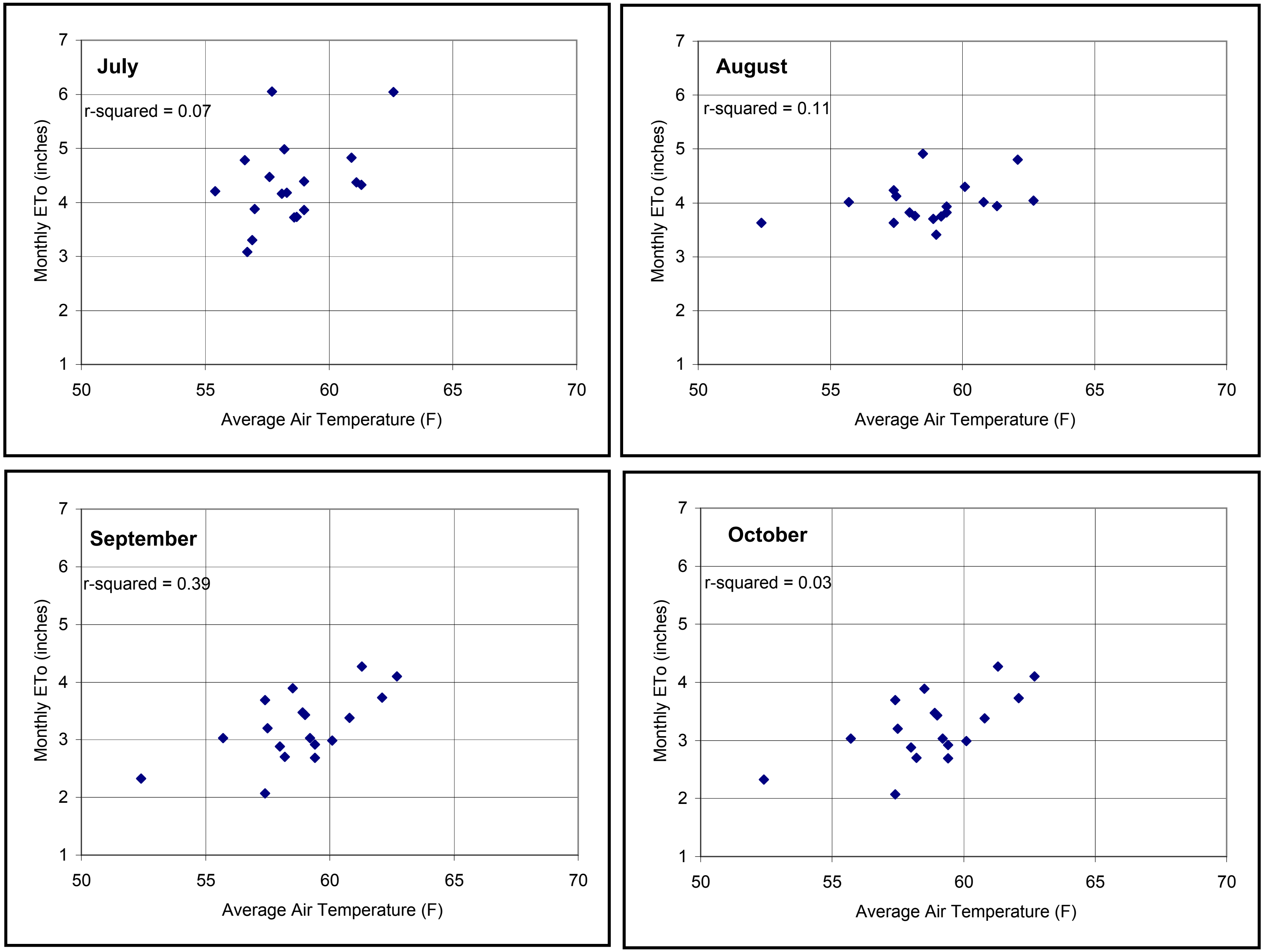

Figure 1. Relation of Monthly Reference Eto and Monthly Average Air Temperature at the Castroville CIMIS station, 1983-2002

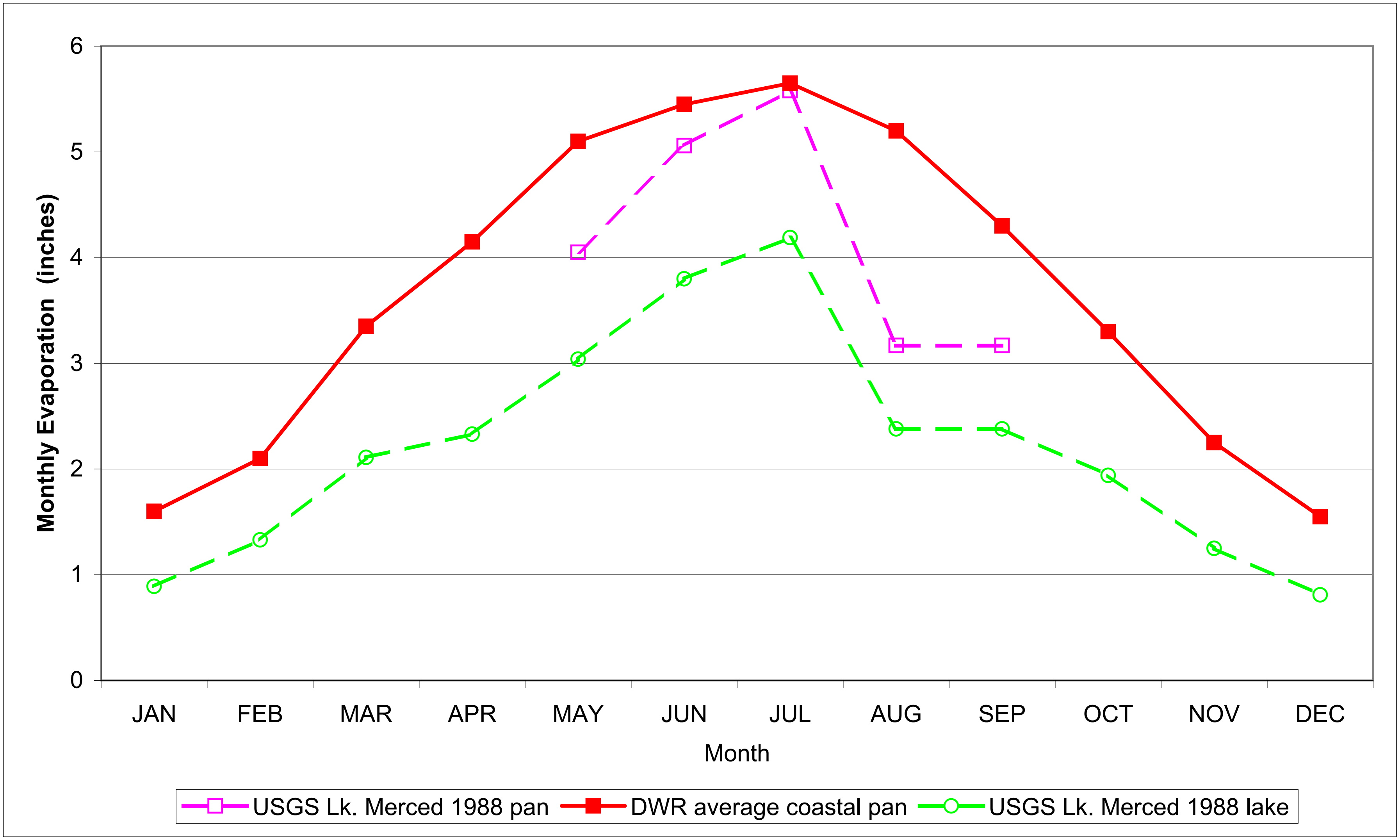

Figure 2. Measured and Estimated Pan and Lake Evaporation at Lake Merced from U. S. Geological Survey Report

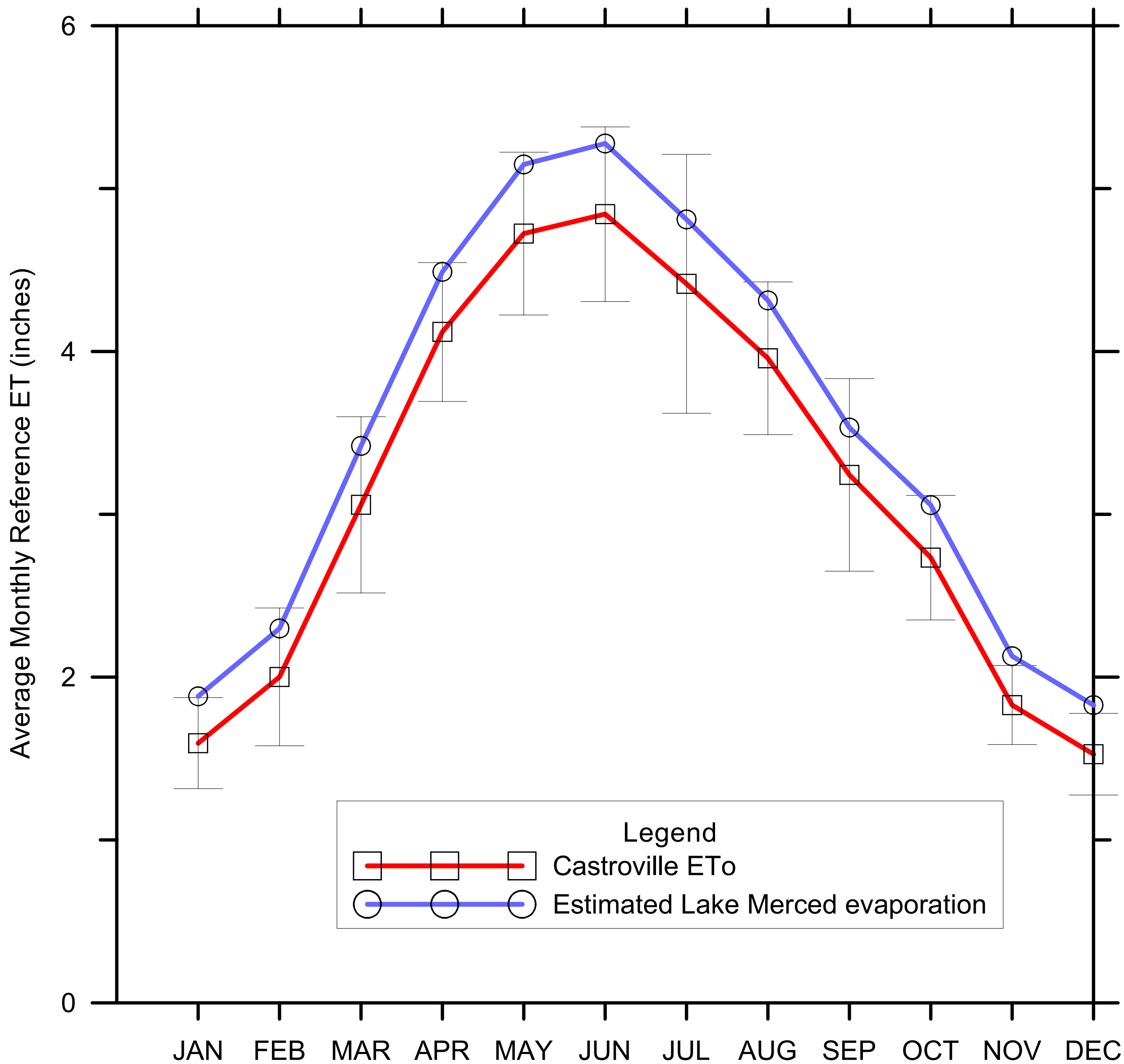

Figure 3. Average Monthly Reference ET at Castroville, 1983-2002 and Associated Estimate of Lake Merced Evaporation