# *Climatological Estimates of Open Water Evaporation from Selected Truckee and Carson River Basin Water Bodies, California and Nevada*

**Justin L. Huntington**
**Daniel McEvoy**

**August 2011**

**Publication No. 41254**

Prepared by
Division of Hydrologic Sciences, Desert Research Institute, Reno, NV

Prepared for
Jeff Boyer, Federal Water Master's Office, TROA Coordinator,
and U.S. Bureau of Reclamation

**THIS PAGE INTENTIONALLY LEFT BLANK**

## ABSTRACT

Historically, evaporation from lakes and reservoirs in the Truckee-Carson basins has been estimated using pan evaporation information, which is widely known to have significant uncertainty both in magnitude and timing. Reservoir operations and development of new storage and water accounting strategies require more accurate evaporation estimates. The objective of this study was to estimate mean monthly and mean annual net open water evaporation from lakes and reservoirs in the Truckee-Carson basins from 2000 to 2009 using available land-based weather data with a widely accepted approach that is relatively accurate on both a seasonal and annual basis. The reservoirs and lakes where evaporation was estimated in this report are Stampede, Boca, Prosser, Martis, and Lahontan reservoirs; and Lake Tahoe, Donner Lake, and Independence Lake. The Complementary Relationship Lake Evaporation (CRLE) model, an open water evaporation model that accounts for water temperature, albedo, emissivity, and heat storage effects to produce realistic operational estimates of monthly evaporation was used. Because the CRLE is insensitive to differences in temperature, humidity, and wind speed from land to water, it overcomes shortcomings of other estimation methods requiring accurate over water humidity and wind speed. The CRLE model instead relies on the strength of the available energy approach, in which wind speed and dewpoint are not used directly. Application of the CRLE model required acquiring local weather data (e.g., solar radiation, air temperature, and dewpoint) from weather stations near the reservoirs and lakes of interest. Proxies for dewpoint were developed where measurements did not exist. These weather variables were input to the CRLE model to estimate monthly evaporation from 2000 to 2009 at each water body. Mean monthly evaporation during winter and spring periods was adjusted to account for ice cover using ice-cover observations from satellite images. Net evaporation, defined as the difference between ice-cover adjusted evaporation and precipitation, was computed by estimating mean monthly PRISM precipitation for each water body. Validation of CRLE-estimated evaporation was performed using previous evaporation estimates in Nevada and California. Results of the validation show that annual CRLE evaporation estimates are almost entirely within ±10% of independent evaporation estimates and generally capture the seasonal trend in evaporation. Validation highlighted the CRLE model's ability to predict annual and seasonal evaporation using limited weather data. While the CRLE model does have limitations, it is the most appropriate approach with the current data limitations – only land based weather data are available at this time. Annual and seasonal evaporation estimates from water bodies of interest could be improved with the development of a reservoir meteorological network to collect data needed in more complex and possibly more accurate approaches.

THIS PAGE INTENTIONALLY LEFT BLANK

## CONTENTS

ABSTRACT ........ iii
LIST OF FIGURES ........ vi
LIST OF TABLES ........ vii
INTRODUCTION ........ 1
OBJECTIVE ........ 1
APPROACH ........ 1
METHODS ........ 4
APPLICATION ........ 5
  Lake Tahoe ........ 11
  Boca ........ 11
  Stampede ........ 11
  Prosser ........ 11
  Martis ........ 12
  Independence ........ 12
  Donner ........ 12
  Lahontan ........ 12
RESULTS ........ 12
  Evaporation ........ 12
  Net Evaporation ........ 18
  Validation ........ 25
  Limitations of Methodology ........ 27
CONCLUSIONS ........ 31
REFERENCES ........ 32

## LIST OF FIGURES


1. Study area showing reservoirs and lakes for which evaporation estimates are made. ............. 2
2. Truckee River basin water bodies and weather stations used for estimating open water evaporation. .......... 7
3. Carson River basin water body and weather stations used for estimating open water evaporation. .......... 8
4. Mean monthly dewpoint depression from the Truckee GSOD airport weather station used for estimating dewpoint at water bodies absent of measurements. .......... 9
5. Mean monthly evaporation (2000 to 2009) for all water bodies, where the impact of water or thermal mixing depth on the timing of evaporation is clearly evident by the lag in evaporation compared to the Boca pan derived estimate. .......... 13
6. Landsat TM image acquired on January, 19, 2007 illustrating ice cover over Boca and Prosser reservoir. .......... 15
7. Two Landsat TM scenes acquired in winter (left) and spring (right) of 2007 (January 19 and March 24), where it is evident that water bodies of Martis, Prosser, Boca, and Independence are ice covered during January, and Independence Lake has ice cover in March. .......... 16
8. Two Landsat TM scenes acquired on April 9 (left) and May 11 (right) 2007 where it is evident that Independence Lake is ice covered in April due to its small size, high elevation, and heavy snowpack, and by May all water bodies are ice free. .......... 17
9. Mean monthly evaporation (2000-2009) for all water bodies adjusted for ice cover. .......... 18
10. Mean annual gridded 400 m spatial resolution PRISM precipitation data (1971-2000) for Truckee basin water bodies of interest. .......... 20
11. Mean annual 1971-2000 PRISM precipitation contours for Lake Tahoe. .......... 21
12. Mean monthly net evaporation for each water body computed as the difference between mean monthly evaporation (adjusted for ice cover) and precipitation. .......... 25
13. Results of CRLE modeled evaporation compared with previously published estimates. .......... 27
14. Mean monthly evaporation for several different methods for Lake Tahoe. .......... 30

## LIST OF TABLES

1. Weather stations and measured weather variables used for application of the CRLE model........ 6
2. Water bodies and respective weather station and weather variables used for CRLE modeling. ........ 9
3. Numeric values of mean monthly dewpoint depression from the Truckee GSOD airport weather station used for estimating dewpoint at water bodies absent of measurements........ 10
4. Summary of the water body and respective area weighted depths, salinities, altitude, and latitude used as input parameters in the CRLE model. ........ 11
5. Mean monthly and mean annual evaporation rates (in/month) for each water body from 2000 to 2009........ 13
6. Percentage of Landsat TM images per month with ice cover from 1984 to 2009 for each water body. ........ 17
7. Mean monthly evaporation (in/month) adjusted for ice cover........ 18
8. PRISM mean monthly (1971 to 2000) precipitation for each water body derived from spatially averaging 400 m resolution gridded PRISM data to water body boundaries........ 19
9. Mean monthly PRISM precipitation fractions for each water body and respective weather station. ........ 22
10. Scanned table of Boca pan evaporation estimates (obtained from the Federal Water Master's Office) currently used for reservoir operations........ 24
11. Mean monthly net evaporation for each water body computed as the difference between mean monthly evaporation (adjusted for ice cover) and precipitation (Tables 7 and 8). ........ 24
12. Results of CRLE modeled evaporation compared with previously published estimates........ 28

## ACRONYMS

| | |
|---|---|
| $a$ | = albedo |
| $\alpha$ | = Priestly-Taylor coefficient |
| AGRIMET | = U.S. Bureau of Reclamation Agricultural Weather Network |
| ASCE-EWRI | = American Society of Civil Engineers – Environmental Water Resources Institute |
| $b_1$ | = calibration constant |
| $b_2$ | = calibration constant |
| CR | = Complementary Relationship |
| CRAE | = Complementary Relationship Areal Evapotranspiration |
| CRLE | = Complementary Relationship Lake Evaporation |
| COOP | = Cooperative Station |
| $\Delta$ | = slope of the saturation vapor pressure curve |
| $\Delta_w$ | = wet environment slope of the saturation vapor pressure curve |
| $e_a$ | = mean actual vapor pressure |
| $e_s$ | = saturation vapor pressure |
| $E$ | = evaporation |
| EBBR | = energy balance Bowen ratio |
| $E_p$ | = potential evapotranspiration |
| $ET$ | = evapotranspiration |
| $E_w$ | = wet environment evaporation |
| $\gamma$ | = psychrometric constant |
| $G$ | = heat storage |
| GIS | = Geographic Information System |
| GSOD | = Global Summary of the Day |
| $k$ | = storage constant |
| $K_o$ | = dewpoint depression |
| NASA | = National Aeronautics and Space Administration |
| NRCS | = Natural Resource Conservation Service |
| *PPT* | = precipitation |
| *PRISM* | = Precipitation Regression on Independent Slopes Model |
| RAWS | = Remote Automated Weather Station |
| $R_n$ | = net radiation |
| $R_s$ | = solar radiation |
| $R_w$ | = net radiation for a water surface |
| SNOTEL | = Snow Telemetry |
| $t$ | = time (months) as a function of salinity and lake depth |
| $T_a$ | = air temperature |
| $T_{dew}$ | = dewpoint temperature |
| $T_{min}$ | = minimum air temperature |
| TM | = Thematic Mapper |
| TROA | = Truckee River Operating Agreement |
| USBR | = U.S. Bureau of Reclamation |
| USCG | = U.S. Coast Guard |
| USGS | = U.S. Geological Survey |

## INTRODUCTION

Reservoir operations and development of new storage and water accounting strategies require estimates of evaporation. Historically, evaporation from lakes and reservoirs has been estimated using pan evaporation information, which is widely known to have significant uncertainty both in magnitude and timing (*Hounam, 1973; Morton, 1979*). Evaporation pans can over-estimate lake or reservoir evaporation by 25 to 100% when compared to water or energy balance estimates of evaporation (*Kohler et al., 1959; Sellers, 1965*). Heat storage in reservoirs can alter both the rate and timing of evaporation, depending on the volume, geometry, clarity, and surrounding environment of the water body. For shallow water bodies, heat storage impact on seasonal evaporation is minor; however, it can be significant for deep water bodies. For example, recent research has found that peak evaporation of Lake Tahoe actually occurs from September to November (*Trask, 2007*), rather than in summer months as pan evaporation estimates would suggest. Similar results were found by Allander et al. (*2009*) for Walker Lake, Nevada. Furthermore, freezing conditions limit use of the pan evaporation method to less than half of the year in the Truckee-Carson basins. A much more serious problem in estimating evaporation over large, open water bodies is the lack of available water-based climatological observations. Because of these limitations with pan evaporation estimates, a method is desired that is robust, relies on commonly available climatological observations, is relatively insensitive to contrasts between open-water and land environments, and that accounts for heat storage.

## OBJECTIVE

Currently, evaporation estimates for lakes and reservoirs in the Truckee-Carson basins are based on pan evaporation data. The objective of this study was to estimate mean monthly and mean annual net open-water evaporation from lakes and reservoirs in the Truckee-Carson basins using available land-based weather data and a widely accepted approach that is accurate on both seasonal and annual timescales. The reservoirs and lakes where net evaporation estimates are made in this report are Stampede, Boca, Prosser, Martis, and Lahontan reservoirs; and Lake Tahoe, Donner Lake, and Independence Lake (Figure 1).

## APPROACH

Most approaches for estimating open water evaporation are based on the aerodynamic mass transfer method, the energy balance Bowen ratio (EBBR), Priestley-Taylor (*1972*) available energy, or on Penman's (*1948*) combination energy-mass transfer methods such as those proposed by Harbeck (*1962*), Kohler and Parmele (*1967*), and Brutsaert and Yeh (*1976*). There are several limitations in the successful application of these methods when over-water weather data is not readily available. For example, over-water wind speed, vapor pressure, and water surface temperature must be measured for successful application of aerodynamic mass transfer methods. In addition to these requirements, heat advection of both


Figure 1. Study area showing reservoirs and lakes for which evaporation estimates are made.

into and out of the water body, heat storage, and net radiation must be estimated or measured for successful application of the EBBR approach. For operational purposes, where daily or even hourly evaporation estimates are needed, the aerodynamic mass transfer approach seems most useful, as heat storage is not required, and, overall, it requires the fewest input data of any of these evaporation estimation methods. However, none of these over water measurements are currently available for Truckee or Carson open water bodies. The aerodynamic mass transfer approach has been compared to energy balance (*Harbeck, 1962*) and eddy covariance Bowen ratio (*Allan and Tasumi, 2005*) estimates of evaporation with much success. A simplified approach combining these estimation methods was developed to estimate open water evaporation for practical and operational purposes (*Morton, 1983*). This simplified approach, called the complementary relationship (CR), is based on the combined energy and aerodynamic equations with a simple heat storage procedure.

The CR approach relies on feedbacks between the over-passing air and the evaporating surface, and between evaporation ($E$) and potential evaporation ($E_p$). Simply stated, when there is ample water available, $E$ increases and approaches the $E_p$. When water is limiting and available energy is fairly constant in space, energy that could have been used by $E$ is instead used in the production of sensible heat flux; the vapor pressure deficit then increases due to reduced $E$, thus elevating $E_p$ due to hotter and drier air. The CR has been extensively applied to estimate open water $E$ and evapotranspiration ($ET$), and tested against energy and water balance estimates of open water $E$ (*Morton 1979; Morton 1983a; Morton 1986*) and $ET$ (*Morton, 1983b; Brutsaert and Stricker, 1979; Hobbins et al., 2001; Ozdogan and Salvucci, 2004; Kahler and Brutsaert, 2006; Yang et al., 2006; Huntington et al., 2011*). Results from these studies all support a realistic, physical basis of the CR (*Szilagyi and Jozsa, 2008; Huntington et al., 2011*), and many have shown that the CR performs well for estimating reservoir and lake evaporation using limited weather data (*Morton 1986; Sadek et al., 1997; DosReis and Dias, 1998; Jones et al., 2001; Vallet-Coulomb, 2001*).

The concept of the CR, which centers on feedbacks between land and the near-surface boundary layer, provides the basis for the Complementary Relationship Areal Evapotranspiration model (CRAE) (*Morton, 1983b*). Changes in land-based measurements of temperature and humidity occur as an air mass passes from the land to the open water environment. As the air passes from land to water, it becomes cooler and wetter. Development of the CRAE model led to a more specific model for open water-evaporation, known as the Complementary Relationship Lake Evaporation (CRLE) model (*Morton, 1983a; Morton et al., 1985; Morton, 1986*), which accounts for water temperature, albedo, emissivity, and heat storage effects for realistic operational estimates of monthly evaporation.

Morton's (*1983*) CRLE parameterization of $E_p$ and wet environment evaporation ($E_w$) was chosen, as it is less sensitive to uncertainties in dewpoint temperature and open-water wind speed than other methods of estimating $E_p$, such as the Penman (*1948*) equation. Because the CRLE is less sensitive to differences in temperature, humidity, and wind speed between land and water, it overcomes shortcomings of the mass transfer method and combination approach, and instead relies on the strength of the Priestly-Taylor available energy approach, in which wind speed and dewpoint are not used directly. Terms in the Priestly-Taylor equation (*Priestly and Taylor, 1972*) for computing $E_w$, on which the CRLE approach is based, were calibrated to water budget estimates of evaporation using land-based air temperature, dew point temperature, and solar radiation; therefore, it is well suited to be applied when no over-water weather data are available, such as in this study. Finally, Morton's (*1983*) CRLE parameterization of $E_p$ and $E_w$ has been well-tested and extensively applied in operations and modeling of open-water evaporation (*Morton, 1986; DosReis and Dias, 1998; Sadek et al., 1997; Jones et al., 2001; Vallet-Coulomb et al., 2001*).

**METHODS**

The mathematical formulation of the CRLE model approach is discussed at length in Morton (*1983a*): only a brief summery will be presented below. The CRLE approach uses a numerical energy-aerodynamic approach by iteratively solving the energy balance and vapor transfer equations for $E_p$ to obtain the equilibrium surface temperature: the surface temperature at which the energy balance equation and the vapor transfer equation for a moist surface (wet environment) give the same result. The details of this iterative solution are described in Morton (*1983a, page 22*). This wet-environment equilibrium surface temperature is then used to compute the slope of the saturation vapor pressure curve in the Priestley-Taylor equation. The Priestley-Taylor equation is defined as

$$E_w = \frac{\alpha\Delta(R_n - G)}{(\Delta + \gamma)}$$

where $\alpha$ is the Priestley-Taylor coefficient of 1.26 derived from calibration over water and 'wet' land surfaces, $\Delta$ is the slope of the saturation vapor pressure curve, $\gamma$ is the psychometric constant, $R_n$ is the net radiation, and $G$ is the heat storage, such that $R_n$-$G$ is available energy. Notice that the Priestley-Taylor equation does not include a vapor pressure deficit term (i.e., saturated vapor pressure, $e_s$, minus actual vapor pressure, $e_a$), making it an equilibrium, or wet-environment, equation in which advection of energy (hot dry air) over the water surface is negligible. However, $\alpha>1$ indicates that regional advection is accounted for in the Priestley-Taylor equation; otherwise, if evaporation was strictly limited to the available energy, then $\alpha=1$. Morton (*1979*) identified a few limitations to the direct application of the Priestley-Taylor equation to open water bodies: (1) the slope of the vapor pressure curve ($\Delta$) is a function of surface temperature, so a wet-environment surface temperature should be used to compute $\Delta$ instead of an arid, land-based air temperature; (2) it does not take into account the impact of surface temperature change on net longwave radiation loss; and (3) there is no direct method to account for heat storage in this formulation. To account for these limitations Morton (*1983a*) modified the Priestley-Taylor equation as

$$E = b_1 + b_2 \frac{\Delta_w(R_w - G)}{(\Delta_w + \gamma)}$$

where $R_w$ is the net radiation for a water surface in which net longwave radiation loss is accounted for (*Morton, 1983a*), calibration constants $b_1$ and $b_2$ are 13 w/m$^2$ and 1.12, respectively, and $\Delta_w$ is the wet-environment slope of the saturation vapor pressure curve computed with the wet-environment surface temperature obtained from an iterative solution as described above.

A similar iterative approach for estimating the wet environment surface temperature and application of the modified Priestley-Taylor equation with $\Delta_w$ has shown to improve evapotranspiration predictions when compared to regional scale water balance data (*Szilagyi and Jozsa, 2008*) and eddy correlation evapotranspiration data collected in eastern Nevada (*Huntington et al., 2011*). Constants $b_1$ and $b_2$ and constants required to compute $R_w$ were calibrated using water-budget estimates of lake evaporation from Pyramid and Winnemucca lakes, NV, along with five other lakes in the U.S. The heat storage term ($G$) is solved for using an approach outlined by Morton (*1983a, pages 90-92*) and Morton (*1986, pages 375-376*), in which absorbed short wave solar radiation ($R_{s*}(1\text{-}a)$, where $a$ is the water albedo) is lagged by $t$ months as a fraction, where $t$ is a function of salinity and lake depth. A hypothetical, linear, heat-storage reservoir is used to lag absorbed shortwave solar radiation, similar to the Muskingum's routing method (*DosReis and Dias, 1998*). The functions and constants for $t$ and storage constant $k$, outlined by Morton (*1986*), were developed by calibration based on monthly water-balance estimates of evaporation from nine lakes, including Pyramid and Walker lakes, NV.

## APPLICATION

The application and validation of the CRLE model required weather data, including solar radiation, air temperature, and dewpoint, which were acquired from weather stations near the reservoirs and lakes of interest (Table 1). Figures 2 and 3 illustrate the weather stations used to develop input datasets for the CRLE model. Daily measurements of solar radiation ($R_s$), air temperature ($T_a$), and dew point temperature ($T_{dew}$) were acquired and checked for quality assurance and control according to Allen (*1996*) and ASCE-EWRI (*2005*). Table 2 lists the weather station and station variables used for each water body. Only three stations – Lake Tahoe University of California-Davis Coast Guard pier (USCG), Truckee Airport Global Summary of the Day (GSOD), and Fallon AGRIMET – measure $T_{dew}$; therefore $T_{dew}$ was estimated at all other weather stations used for the CRLE model input (Boca, Donner, Independence Lake Natural Resource Conservation Service [NRCS] Snow Telemetry [SNOTEL], Lahontan Dam).

$T_{dew}$ is defined as the temperature to which a parcel of air must be cooled to become saturated with water vapor. Daily $T_{min}$ commonly approaches $T_{dew}$ due to conditioning of the near surface boundary layer from evaporation and transpiration, especially during early morning when wind is calm and soil moisture is high. There is seasonality of the mean monthly difference between $T_{min}$ and $T_{dew}$, defined as the dewpoint depression ($K_o$), as seen in Table 3 and Figure 4. For frost and dew (winter and spring) periods $K_o$<0, while in drier spring and summer periods $K_o$>0. It is common in arid and semiarid regions to have $T_{dew}$ of 2°C to 5°C below $T_{min}$ under relatively well watered conditions (*Allen, 1996, ASCE-EWRI 2005*). In this report, mean monthly dewpoint depression was used to estimate humidity of the near surface air mass at stations where $T_{dew}$ is not measured, using $T_{dew} = T_{min} - K_o$, where $T_{min}$ is the daily minimum air temperature (°C), and $K_o$ is the mean monthly dew point depression derived from Truckee GSOD station data (Figure 4, Table 3). The mean monthly dewpoint depression for the Truckee GSOD station ranges from -2.1°C to 3.3°C, with a mean annual value of 0.4°C. Several recent studies show good skill in estimating evaporation and transpiration when using generalized mean monthly dewpoint depression to estimate humidity (*Crago et al., 2010; Huntington and Allen, 2010*).

Table 1. Weather stations and measured weather variables used for application of the CRLE model.

| **Weather Station** | **Latitude** | **Longitude** | **Measured Weather Variables used for Application and Validation of the CRLE Model** |
|---|---|---|---|
| USCG Tahoe Pier | 39.180 | -120.120 | $R_s$, $T_a$, $T_{dew}$ |
| Stampede RAWS | 39.483 | -120.075 | $R_s$ |
| Tahoe City COOP | 39.168 | -120.143 | $T_a$ |
| Boca COOP | 39.389 | -120.094 | $T_a$ |
| Truckee Airport | 39.310 | -120.130 | $T_a$, $T_{dew}$ |
| Independence NRCS Snotel | 39.450 | -120.300 | $T_a$ |
| Donner COOP | 39.324 | -120.233 | $T_a$ |
| Lahontan Dam COOP | 39.469 | -119.064 | $T_a$ |
| Fallon Agrimet | 39.458 | -118.774 | $R_s$, $T_a$, $T_{dew}$ |
| Sutcliff USGS | 39.950 | -119.610 | $T_a$ |
| Walker Lake USGS Bowen | 38.745 | -118.719 | $R_s$, $T_a$, $T_{dew}$ |
| Tahoe Buoy 1 | 39.153 | -120.000 | $T_a$, $T_{dew}$, wind |
| Tahoe Buoy 2 | 39.109 | -120.011 | $T_a$, $T_{dew}$, wind |
| Tahoe Buoy 3 | 39.110 | -120.075 | $T_a$, $T_{dew}$, wind |
| Tahoe Buoy 4 | 39.155 | -120.072 | $T_a$, $T_{dew}$, $T_{skin}$, wind |

Due to the lack of $R_s$ measurements, a compiled $R_s$ dataset ($R_s$ from the Stampede Remote Automated Weather Stations (RAWS) station from 2000 to 2003, and $R_s$ from the USCG station from 2004 to 2009) was used for each of the Truckee River basin water bodies. The USCG measured $R_s$ was chosen over Stampede RAWS measured $R_s$ from 2004 to 2009 due to very poor quality measurements at the Stampede RAWS station in those years.

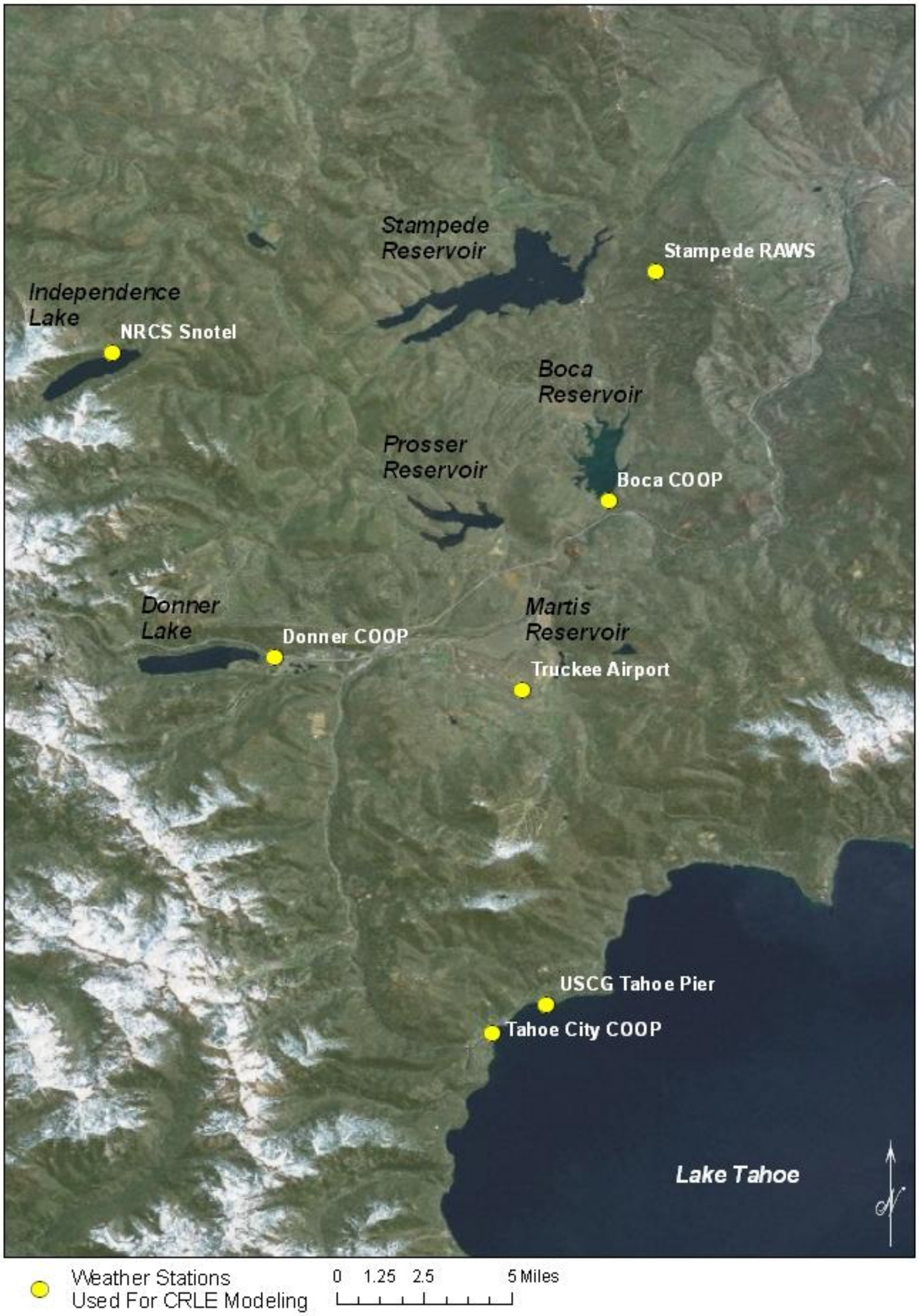


Figure 2. Truckee River basin water bodies and weather stations used for estimating open water evaporation.


Figure 3. Carson River basin water body and weather stations used for estimating open water evaporation.

Table 2. Water bodies and respective weather station and weather variables used for CRLE modeling.

| Water Body | Solar Radiation Station ($R_s$) | Temperature Station for Computing Air Temperature ($T_a$) and Dewpoint Temperature ($T_{dew}$) | Dewpoint Station ($T_{dew}$) for Computing Dewpoint depression ($K_o$) |
|---|---|---|---|
| Lake Tahoe | Stampede RAWS (2000-2003) / Lake Tahoe UC Davis Coast Guard pier (2004-2009) | Tahoe City COOP | Truckee GSOD (2000-2003) / Lake Tahoe UC Davis Coast Guard pier (2004-2009) |
| Boca | Stampede RAWS (2000-2003) / Lake Tahoe UC Davis Coast Guard pier (2004-2009) | Boca COOP | Truckee GSOD |
| Stampede | Stampede RAWS (2000-2003) / Lake Tahoe UC Davis Coast Guard pier (2004-2009) | Boca COOP | Truckee GSOD |
| Prosser | Stampede RAWS (2000-2003) / Lake Tahoe UC Davis Coast Guard pier (2004-2009) | Boca COOP | Truckee GSOD |
| Martis | Stampede RAWS (2000-2003) / Lake Tahoe UC Davis Coast Guard pier (2004-2009) | Truckee GSOD | Truckee GSOD |
| Independence | Stampede RAWS (2000-2003) / Lake Tahoe UC Davis Coast Guard pier (2004-2009) | Independence NRCS Snotel | Truckee GSOD |
| Donner | Stampede RAWS (2000-2003) / Lake Tahoe UC Davis Coast Guard pier (2004-2009) | Donner COOP | Truckee GSOD |
| Lahontan | Fallon AGRIMET (2000-2009) | Lahontan Dam COOP | Fallon AGRIMET |

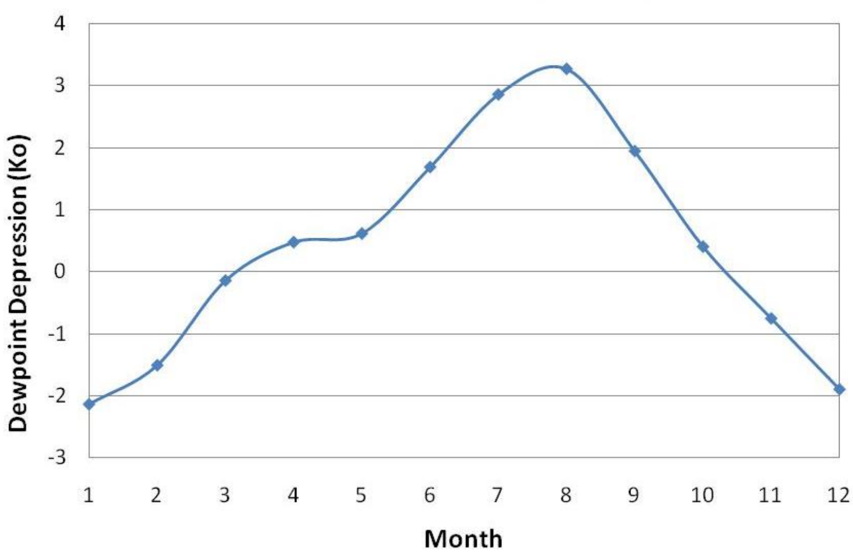


Figure 4. Mean monthly dewpoint depression from the Truckee GSOD airport weather station used for estimating dewpoint at water bodies absent of measurements.

Table 3. Numeric values of mean monthly dewpoint depression from the Truckee GSOD airport weather station used for estimating dewpoint at water bodies absent of measurements.

| Month | Mean $T_{min}$ (C) | Mean $T_{dew}$ (C) | Mean Dewpoint Depression, $T_{min}$-$T_{dew}$ (C) |
|---|---|---|---|
| 1 | -8.0 | -5.9 | -2.1 |
| 2 | -7.0 | -5.5 | -1.5 |
| 3 | -4.8 | -4.6 | -0.1 |
| 4 | -2.7 | -3.2 | 0.5 |
| 5 | 1.0 | 0.4 | 0.6 |
| 6 | 3.6 | 1.9 | 1.7 |
| 7 | 6.6 | 3.8 | 2.9 |
| 8 | 5.2 | 2.0 | 3.3 |
| 9 | 1.5 | -0.4 | 1.9 |
| 10 | -2.3 | -2.7 | 0.4 |
| 11 | -4.8 | -4.0 | -0.8 |
| 12 | -7.3 | -5.4 | -1.9 |

As a required input parameter in the CRLE model, estimated mean annual (2000 to 2009) area weighted water depths for Prosser, Martis, Boca, and Stampede reservoirs were computed using volume-area-stage relationships obtained from the U.S. Bureau of Reclamation (USBR). The average depth of the water body specified in the CRLE model assumes a well-mixed water body. In the case of relatively shallow reservoirs and lakes, this assumption is likely valid, however, if the water body is very deep or not well mixed, for example Lake Tahoe, an effective thermal mixing depth was assumed. The effective thermal mixing depth was approximated to be 50 m for Lake Tahoe (*Tilzer and Goldman, 1978; Dillon and Powel, 1976*). The estimated water body depth primarily impacts the timing of monthly evaporation, therefore, the seasonality of modeled evaporation rates were compared to previous evaporation studies to ensure congruency. For example, Trask (*2007*) illustrated that peak evaporation from Lake Tahoe occurs in September and October due to heat storage. The estimated effective thermal mixing depth of 50 m for Lake Tahoe resulted in CRLE modeled peak evaporation occurring during this same period.

As another required input parameter in the CRLE model, average salinities for each water body were estimated from web reviews. A summary of water body and respective area weighted depths, salinities, altitude, and latitude used as input parameters in the CRLE model is shown in Table 4. Because the CRLE model operates at monthly time steps all station data was averaged to the month for each year. The following sections describe weather station data used for CRLE input for each reservoir and lake, and describe any assumptions made for application of the modified Priestly-Taylor equation.

Table 4. Summary of the water body and respective area weighted depths, salinities, altitude, and latitude used as input parameters in the CRLE model.

| Water Body | Water Body Latitude | Water Body Altitude (m) | Area Weighted Mean Water Depth (m) | Total Dissolved Solids (mg/L) |
|---|---|---|---|---|
| Lake Tahoe | 39.05 | 1,900 | 50 (assumed effective thermal mixing depth) | 60 |
| Boca | 39.40 | 1,720 | 8.5 | 60 |
| Stampede | 39.70 | 1,814 | 17.1 | 60 |
| Prosser | 39.38 | 1,751 | 9.4 | 60 |
| Martis | 39.32 | 1,776 | 4 | 60 |
| Independence | 39.44 | 2,118 | 14.6 | 60 |
| Donner | 39.32 | 1,823 | 30 | 60 |
| Lahontan | 39.46 | 1,264 | 7 | 300 |

## Lake Tahoe

Weather station data used for Lake Tahoe CRLE model input included $R_s$, $T_a$, and $T_{dew}$ collected at the Lake Tahoe USCG station from 2000 to 2009. These data were complete from 2004 to 2009; however, there were significant missing $T_{dew}$ measurements before this period. Mean monthly dew point depression ($K_o$=$T_{min}$-$T_{dew}$) derived from the Truckee Airport GSOD station was used to compute monthly $T_{dew}$ from 2000 to 2003 as $T_{dew}$ = $T_{min}$-$K_o$. USCG $R_s$ data from 2000 to 2003 were also missing; therefore, these data were estimated from $R_s$ measurements made at the Stampede RAWS station (Figure 2).

## Boca

Weather station data used for the Boca reservoir CRLE model input included $R_s$ measurements from the Stampede RAWS and USCG stations, $T_a$ from the Boca COOP weather station, and dew point depression derived from the Truckee Airport GSOD station. Monthly $T_{dew}$ was then computed for Boca reservoir as $T_{dew}$ = $T_{min}$-$K_o$.

## Stampede

Weather station data used for the Stampede reservoir CRLE model input included $R_s$ measurements from the Stampede RAWS and USCG stations, $T_a$ from the Boca COOP weather station, and dew point depression derived from the Truckee Airport GSOD station. $T_{dew}$ was then computed for Stampede reservoir as $T_{dew}$ = $T_{min}$-$K_o$.

## Prosser

Weather station data used for the Prosser reservoir CRLE model input included $R_s$ measurements from the Stampede RAWS and USCG stations, $T_a$ from the Boca weather station, and dew point depression derived from the Truckee Airport GSOD station. Monthly $T_{dew}$ was then computed for Prosser reservoir as $T_{dew}$ = $T_{min}$-$K_o$.

### Martis

Weather station data used for the Martis reservoir CRLE model input included $R_s$ measurements from the Stampede RAWS and USCG stations, and $T_a$ and $T_{dew}$ from the Truckee Airport GSOD weather station.

### Independence

Weather station data used for the Independence reservoir CRLE model input included $R_s$ measurements from the Stampede RAWS and USCG stations, $T_a$ from the NRCS Independence SNOTEL weather station, and mean monthly dew point depression derived from the Truckee Airport GSOD station. Monthly $T_{dew}$ was then computed for Independence reservoir as $T_{dew} = T_{min}\text{-}K_o$.

### Donner

Weather station data used for the Donner Lake CRLE model input included $R_s$ measurements from the Stampede RAWS and USCG stations, $T_a$ from the Donner Lake State Park COOP weather station, and mean monthly dew point depression derived from the Truckee Airport GSOD station. Monthly $T_{dew}$ was then computed for Donner Lake as $T_{dew} = T_{min}\text{-}K_o$.

### Lahontan

Weather station data used for the Lahontan reservoir CRLE model input included data of $R_s$ from the USBR Fallon AGRIMET station, $T_a$ from the Lahontan Dam COOP weather station, and mean monthly dew point depression derived from the USBR Fallon AGRIMET station (Figure 3). Monthly $T_{dew}$ was then computed for Lahontan reservoir as $T_{dew} = T_{min}\text{-}K_o$.

## RESULTS

### Evaporation

Results of the CRLE modeled evaporation were averaged for each month to compute 2000 to 2009 mean monthly and mean annual evaporation rates for each water body (Tables 2, 4, and 5 and Figures 2 and 3). While mean annual evaporation is very similar for Truckee River basin water bodies, the timing for each is quite different. Figure 5 illustrates mean monthly evaporation for all water bodies, where the impact of water depth or thermal mixing depth on evaporation timing is clearly evident from the shift in peak evaporation compared to the Boca pan-derived estimate. Lake Tahoe has the largest shift and winter evaporation rate due to its large water volume and associated heat storage. In contrast, Martis reservoir's monthly evaporation distribution is similar to the pan-derived estimate due to its shallow depth and limited heat storage potential.

Table 5. Mean monthly and mean annual evaporation rates (in/month) for each water body from 2000 to 2009.

| Water Body | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | Ann |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Boca** | 1.5 | 0.9 | 1.2 | 1.9 | 3.3 | 4.8 | 6.6 | 7.2 | 6.5 | 5.6 | 3.9 | 2.8 | 46.1 |
| **Martis** | 0.9 | 0.9 | 1.7 | 2.8 | 4.7 | 6.2 | 7.6 | 7.3 | 5.9 | 4.3 | 2.5 | 1.5 | 46.3 |
| **Prosser** | 1.5 | 1.0 | 1.2 | 1.8 | 3.3 | 4.8 | 6.6 | 7.2 | 6.5 | 5.6 | 4.0 | 2.8 | 46.1 |
| **Stampede** | 1.7 | 1.1 | 1.2 | 1.8 | 3.1 | 4.5 | 6.3 | 7.0 | 6.5 | 5.7 | 4.2 | 3.1 | 46.1 |
| **Independence** | 1.8 | 1.0 | 1.1 | 1.7 | 3.0 | 4.5 | 6.4 | 7.2 | 6.7 | 5.8 | 4.2 | 3.1 | 46.6 |
| **Donner** | 2.1 | 1.2 | 1.2 | 1.6 | 2.8 | 4.1 | 5.9 | 6.8 | 6.6 | 5.9 | 4.5 | 3.4 | 46.0 |
| **Tahoe** | 3.4 | 2.1 | 1.6 | 1.5 | 2.1 | 3.1 | 4.7 | 5.8 | 6.0 | 6.0 | 5.1 | 4.7 | 46.0 |
| **Lahontan** | 1.3 | 0.9 | 1.4 | 2.4 | 4.2 | 5.8 | 7.9 | 8.1 | 6.8 | 5.5 | 3.5 | 2.2 | 50.0 |

The similarity in mean annual evaporation rate for each water body is primarily due to the fact that the same monthly time series of $R_s$ was used as input to the CRLE, with the exception of Lahontan reservoir. Vallet-Coulomb et al. (*2001*) conducted a sensitivity analysis of the CRLE model and showed that $R_s$ was the most sensitive input variable, where ± 10 % error in $R_s$, $T_a$, and $T_{dew}$ produced evaporation-prediction errors of 6.9%, 2.0%, and 0.4%, respectively. They also showed that CRLE was the least sensitive to input variable uncertainties when compared to the energy balance and Penman methods for estimating evaporation. Given the lack of measured $R_s$ and other input variables at or near the water bodies of interest, using a consistent and quality controlled $R_s$ dataset for all water bodies is currently the best option for CRLE input. It should be noted that a unique $R_s$ dataset was developed for Lahontan reservoir based on the Fallon AGRIMET station.

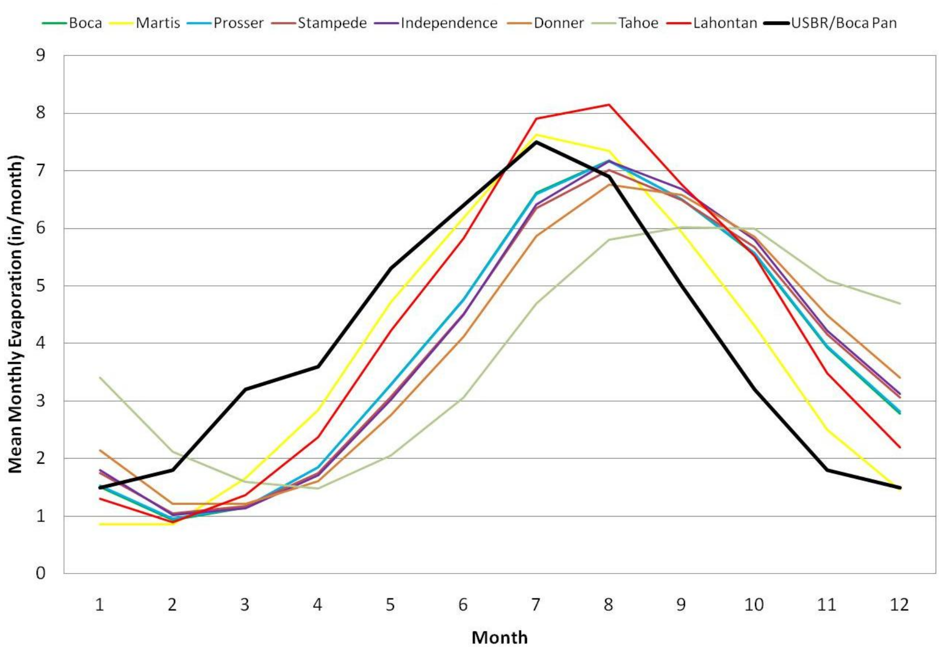


Figure 5. Mean monthly evaporation (2000 to 2009) for all water bodies, where the impact of water or thermal mixing depth on the timing of evaporation is clearly evident by the lag in evaporation compared to the Boca pan derived estimate.

Winter and spring ice cover is common for many of the water bodies in this report; therefore, an approach to estimate the period of ice cover for each water body was developed. Derecki (*1979*) made manual observations of ice cover to adjust winter and spring evaporation rates. This study used observations of ice cover from satellite images. Over 140 Landsat Thematic Mapper (TM) images were analyzed in winter, spring, and fall from 1984 to 2009 to detect ice cover on each water body. This archive of images will be valuable for future evaporation work using surface temperature and energy balance approaches. Image processing techniques were used to develop reflectance band combinations at 30 m spatial resolution such that ice cover was easily detected from simple visual inspection of the images (Figure 6). Given the complexity of identifying thin or patchy ice, verses clearly visible and consistent ice cover, and the complex nature in the development of an automated image classification procedure that accounts for varying water body boundaries, it was assumed that the entire water body was ice covered if ice was clearly visible using the Landsat TM reflectance band combination of 5, 3, and 2 for red, green, and blue channels. This approach is robust because ice or snow is displayed as aqua blue, while ice-free open water is displayed as black. For example, Figure 6 illustrates ice cover over Boca and Prosser reservoirs, but not Stampede. Figures 7 and 8 illustrate four Landsat TM scenes acquired in 2007 (January 19, March 24, April 9, May 11), where it is evident from the aqua blue coloring that small, low elevation (Martis, Prosser, Boca) and high elevation (Independence Lake) water bodies are ice covered (Figure 7). As spring progresses, these water bodies become ice free (Figure 8). Table 6 summarizes the percentage of Landsat TM images per month with ice cover from 1984 to 2009 for each water body.

Results indicate that Independence Lake has the longest period of ice cover, followed by small and shallow water bodies, including Prosser, Martis, and Boca reservoirs. As expected, results indicate that Lake Tahoe and Lahontan reservoir are never ice covered. Ice cover percentages in Table 6 were used to reduce respective CRLE modeled evaporation rates at each water body by calculating a monthly ice-free fraction and then multiplying that fraction by mean monthly evaporation rate for each water body (Table 7, Figure 9). In general, the ice-cover adjusted evaporation rates are consistent with what would be expected, where evaporation rates from smaller water bodies are reduced due to ice cover, while large water bodies with less ice cover show smaller changes in evaporation rates. It should be noted that Martis and Prosser reservoirs have 100% ice cover in January, resulting in zero evaporation for this month. This evaporation estimate may be biased low, reflecting potential inaccuracy in the estimated mean monthly ice cover; however, without any other information on the frequency of ice cover, or documented approach for adjusting evaporation due to ice cover without weather or water temperature information, this remote sensing approach is likely the best at this time.

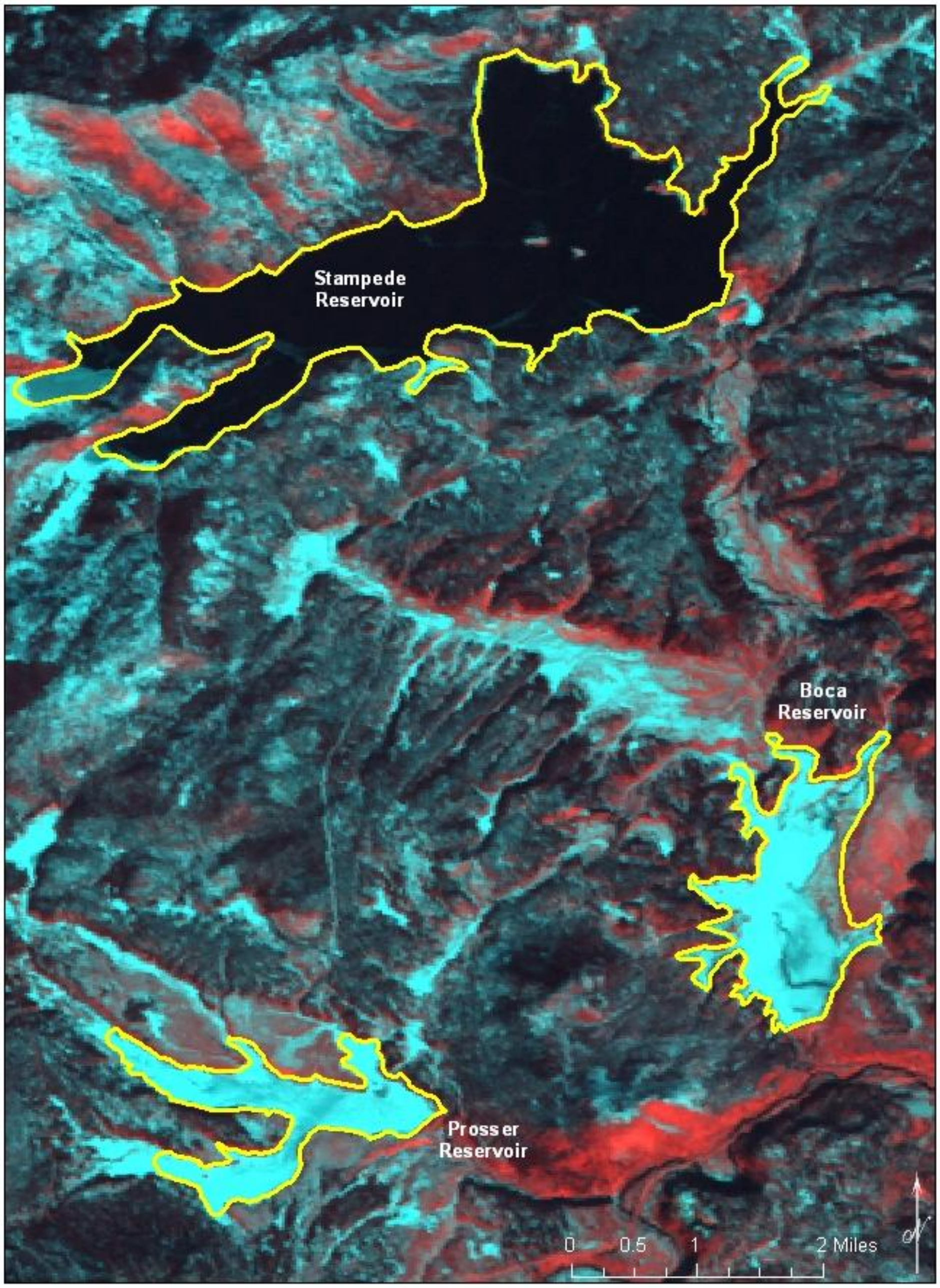


Figure 6. Landsat TM image acquired on January, 19, 2007 illustrating ice cover over Boca and Prosser reservoir. Band combinations of 5, 3, and 2 were used for red, green, and blue channels to clearly identify snow cover and ice, seen as aqua blue.

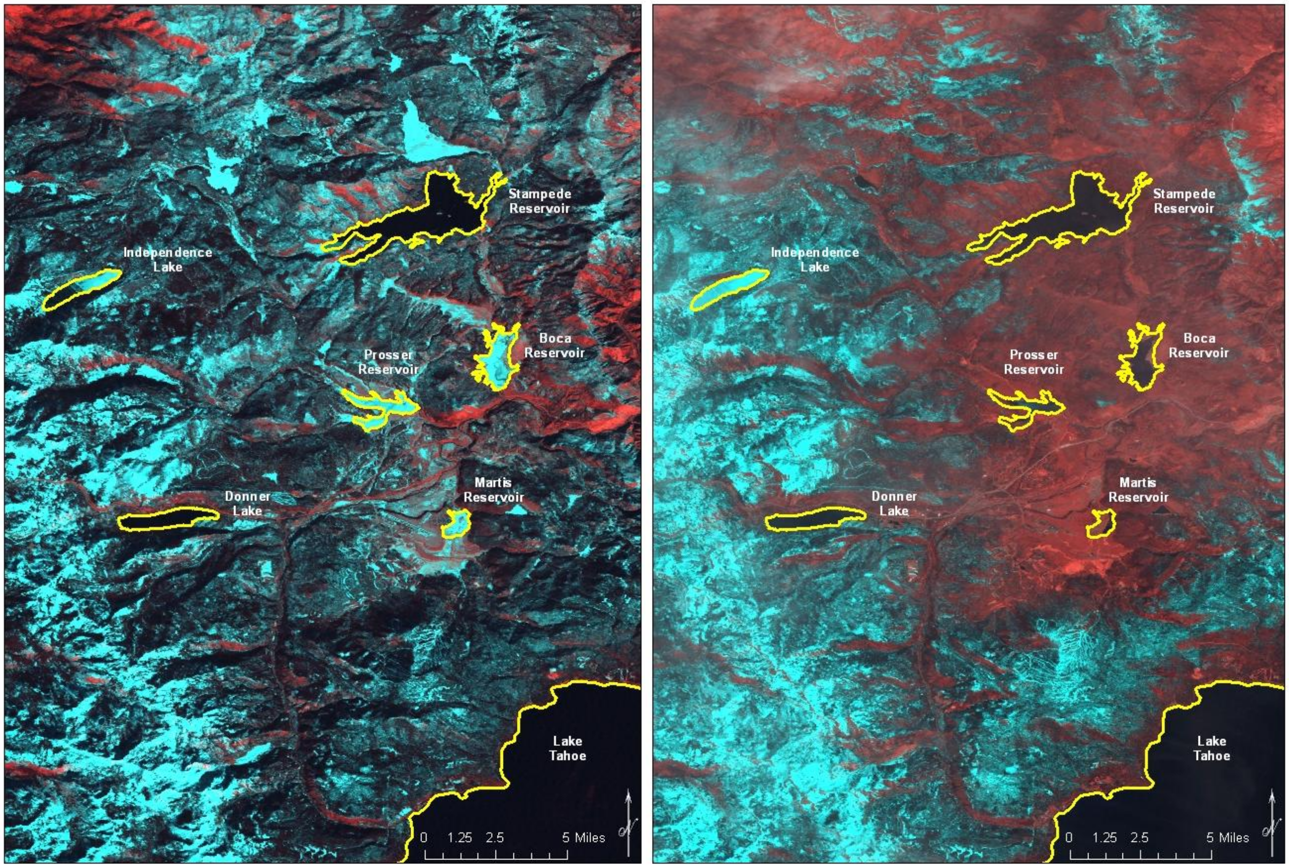


Figure 7. Two Landsat TM scenes acquired in winter (left) and spring (right) of 2007 (January 19 and March 24), where it is evident that water bodies of Martis, Prosser, Boca, and Independence are ice covered during January, and Independence Lake has ice cover in March.

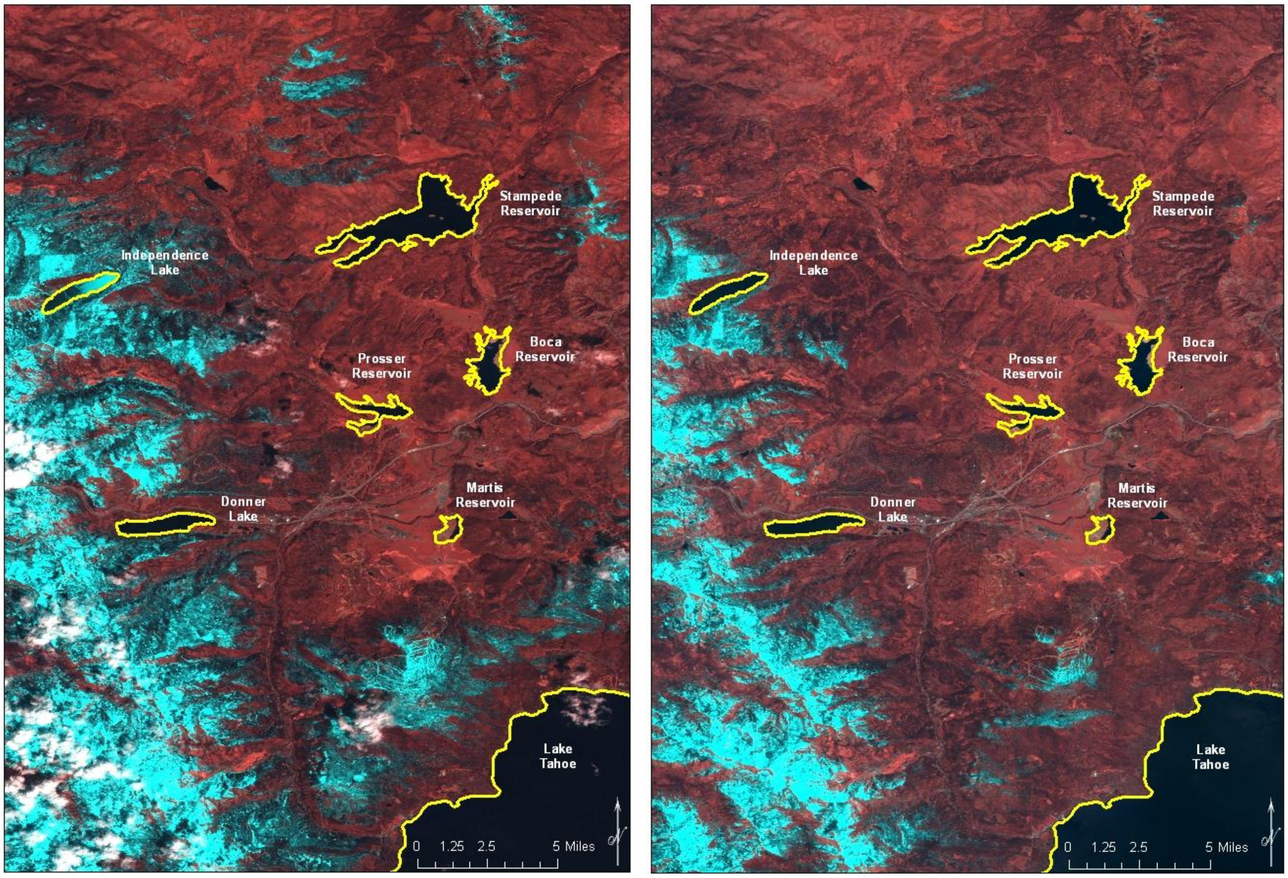


Figure 8. Two Landsat TM scenes acquired on April 9 (left) and May 11 (right) 2007 where it is evident that Independence Lake is ice covered in April due to its small size, high elevation, and heavy snowpack, and by May all water bodies are ice free.

Table 6. Percentage of Landsat TM images per month with ice cover from 1984 to 2009 for each water body.

| Water Body | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Number of Cloud Free Landsat Scenes Evaluated Each Month (1984-2009)** | 11 | 10 | 31 | 27 | 36 | 41 | 40 | 43 | 39 | 33 | 16 | 16 |
| **Percent of Landsat Scenes with Ice Cover Over Water Bodies** | **Jan** | **Feb** | **Mar** | **Apr** | **May** | **Jun** | **Jul** | **Aug** | **Sep** | **Oct** | **Nov** | **Dec** |
| **Boca** | 81.8 | 90 | 39 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 25 |
| **Martis** | 100 | 90 | 52 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 50 |
| **Prosser** | 100 | 90 | 68 | 7.4 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 31 |
| **Stampede** | 9.09 | 80 | 32 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **Independence** | 81.8 | 100 | 84 | 63 | 13.9 | 0 | 0 | 0 | 0 | 0 | 0 | 6.3 |
| **Donner** | 0 | 30 | 9.7 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **Tahoe** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **Lahontan** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

Table 7. Mean monthly evaporation (in/month) adjusted for ice cover.

| Water Body | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | Ann |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Boca** | 0.3 | 0.1 | 0.7 | 1.9 | 3.3 | 4.8 | 6.6 | 7.2 | 6.5 | 5.6 | 3.9 | 2.1 | 42.9 |
| **Martis** | 0.0 | 0.1 | 0.8 | 2.8 | 4.7 | 6.2 | 7.6 | 7.3 | 5.9 | 4.3 | 2.5 | 0.7 | 43.1 |
| **Prosser** | 0.0 | 0.1 | 0.4 | 1.7 | 3.3 | 4.8 | 6.6 | 7.2 | 6.5 | 5.6 | 4.0 | 1.9 | 41.9 |
| **Stampede** | 1.6 | 0.2 | 0.8 | 1.8 | 3.1 | 4.5 | 6.3 | 7.0 | 6.5 | 5.7 | 4.2 | 3.1 | 44.7 |
| **Independence** | 0.3 | 0.0 | 0.2 | 0.6 | 2.6 | 4.5 | 6.4 | 7.2 | 6.7 | 5.8 | 4.2 | 2.9 | 41.5 |
| **Donner** | 2.1 | 0.9 | 1.1 | 1.6 | 2.8 | 4.1 | 5.9 | 6.8 | 6.6 | 5.9 | 4.5 | 3.4 | 45.6 |
| **Tahoe** | 3.4 | 2.1 | 1.6 | 1.5 | 2.1 | 3.1 | 4.7 | 5.8 | 6.0 | 6.0 | 5.1 | 4.7 | 46.0 |
| **Lahontan** | 1.3 | 0.9 | 1.4 | 2.4 | 4.2 | 5.8 | 7.9 | 8.1 | 6.8 | 5.5 | 3.5 | 2.2 | 50.0 |

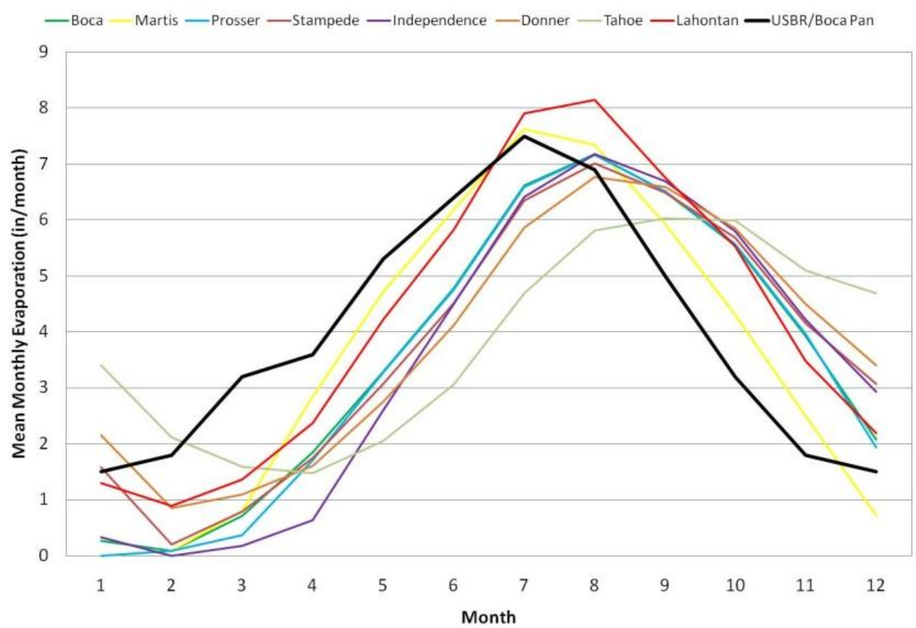


Figure 9. Mean monthly evaporation (2000 to 2009) for all water bodies adjusted for ice cover.

## Net Evaporation

Net evaporation, defined as the difference between evaporation and precipitation, is required for operations, accounting, and water rights analysis. Many of the reservoirs and lakes analyzed in this report do not have precipitation gages, so mean monthly precipitation for each reservoir and lake was estimated using 400 m spatial resolution from 1971 to 2000 PRISM (Precipitation Regression on Independent Slopes Model) precipitation data (*Daly et al., 1994*). The spatial mean for each water body was calculated using GIS (Table 8). Because some water bodies exhibited large spatial variability in precipitation, it was important to have a high-resolution dataset that captured the observed spatial variability in precipitation (Figure 10). For example, Figure 11 illustrates the spatial variability of mean annual precipitation over Lake Tahoe to range from 32.6 in at Tahoe City on the west shore to 17 in at Glenbrook on the east shore. These types of spatial gradients exist in PRISM products, because PRISM uses monthly weather station observations of precipitation, accounting for spatial variability in the x and y directions. Most importantly PRISM relies on multiple precipitation-altitude relationships to account for orographic lifting and condensation due to elevation gradients, while accounting for rain shadows on the lee sides of mountain ranges (*Daly, 1994*).

Table 8. PRISM mean monthly (1971 to 2000) precipitation for each water body derived from spatially averaging 400 m resolution gridded PRISM data to water body boundaries.

| 1971-2000 PRISM Spatially Averaged Water Body Precipitation (in) | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | Ann |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Boca** | 3.8 | 3.7 | 3.3 | 1.2 | 1.0 | 0.6 | 0.4 | 0.5 | 0.9 | 1.5 | 2.8 | 3.3 | 23.0 |
| **Martis** | 5.1 | 5.0 | 4.3 | 1.7 | 1.3 | 0.6 | 0.4 | 0.5 | 1.0 | 1.7 | 3.7 | 4.1 | 29.4 |
| **Prosser** | 5.2 | 4.9 | 4.2 | 1.7 | 1.2 | 0.6 | 0.4 | 0.5 | 1.0 | 1.7 | 3.6 | 4.1 | 29.0 |
| **Stampede** | 5.1 | 5.2 | 4.5 | 1.7 | 1.3 | 0.6 | 0.4 | 0.5 | 1.0 | 1.8 | 3.9 | 4.3 | 30.4 |
| **Independence** | 6.8 | 6.8 | 6.3 | 2.8 | 2.0 | 0.9 | 0.4 | 0.6 | 1.2 | 2.3 | 5.1 | 5.9 | 41.2 |
| **Donner** | 6.8 | 6.7 | 5.9 | 2.5 | 1.7 | 0.8 | 0.5 | 0.6 | 1.1 | 2.3 | 4.9 | 5.5 | 39.4 |
| **Tahoe** | 4.4 | 4.3 | 3.5 | 1.4 | 1.0 | 0.6 | 0.3 | 0.4 | 0.8 | 1.5 | 3.1 | 3.6 | 25.0 |
| **Lahontan** | 0.6 | 0.5 | 0.6 | 0.4 | 0.6 | 0.4 | 0.3 | 0.4 | 0.4 | 0.4 | 0.5 | 0.5 | 5.6 |

Although daily estimates of precipitation were not required for this study in computing net evaporation, in the future, daily precipitation estimates are required for operations and accounting purposes. To address this need, an approach was developed to estimate daily precipitation at each water body, where fractions of the 1971 to 2000 observed precipitation and 1971 to 2000 PRISM spatial average were developed for paired weather stations and water bodies. Daily precipitation at each water body can then be estimated as

$$PPT_{daily\ month\ i} = \left[ \frac{PRISM\, PPT_{monthi}}{StationPPT_{monthi}} \right] * StationPPT_{daily\ month\ i}$$

where $PPT_{daily\ month\ i}$ is the daily precipitation for month *i*, $PRISM\ PPT_{month\ i}$ is the spatially averaged 1971 to 2000 mean monthly precipitation for month *i*, $Station\ PPT_{month\ i}$ is the 1971 to 2000 mean monthly precipitation for month *i*, and $Station\ PPT_{daily\ month\ i}$ is the station's daily precipitation value for month *i*. Mean monthly precipitation and precipitation fractions for respective weather stations are shown in Table 9. For example, at Lake Tahoe, monthly precipitation can be estimated from Tahoe City measured monthly precipitation for a given month *i*, by multiplying the Tahoe City measured monthly precipitation by the fraction of spatially-averaged mean-monthly $PRISM\ PPT_{month\ i}$ over the lake, and Tahoe City COOP $Station\ PPT_{month\ i}$. Because Tahoe City is on the west side of Lake Tahoe, with significantly lower precipitation observed on the east side of Lake Tahoe, the fractions of *PRISM PPT* and Tahoe City COOP *Station PPT* for any given month should be less than 1, as shown in Table 9.

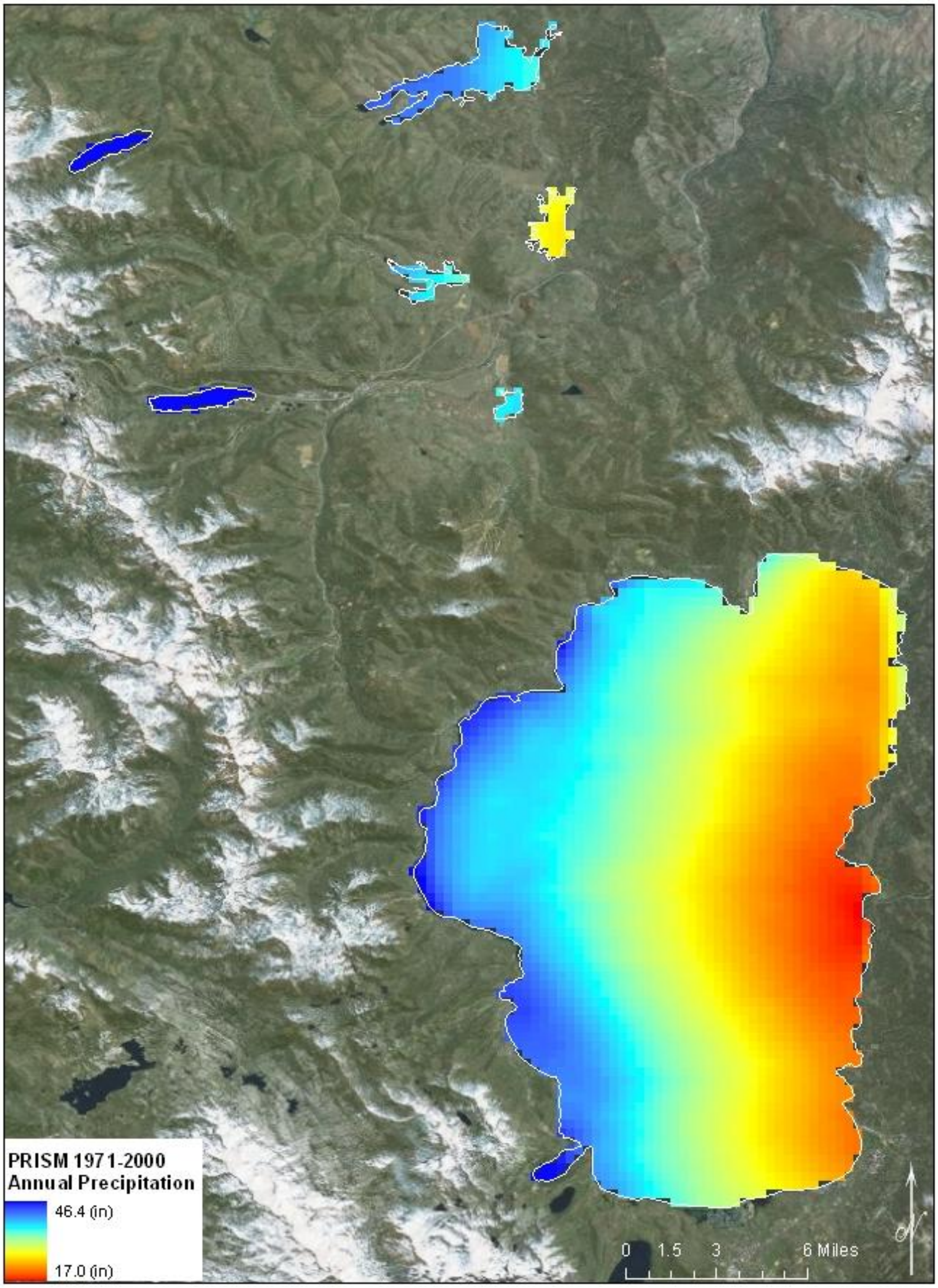


Figure 10. Mean annual gridded 400 m spatial resolution PRISM precipitation data (1971-2000) for Truckee basin water bodies of interest.

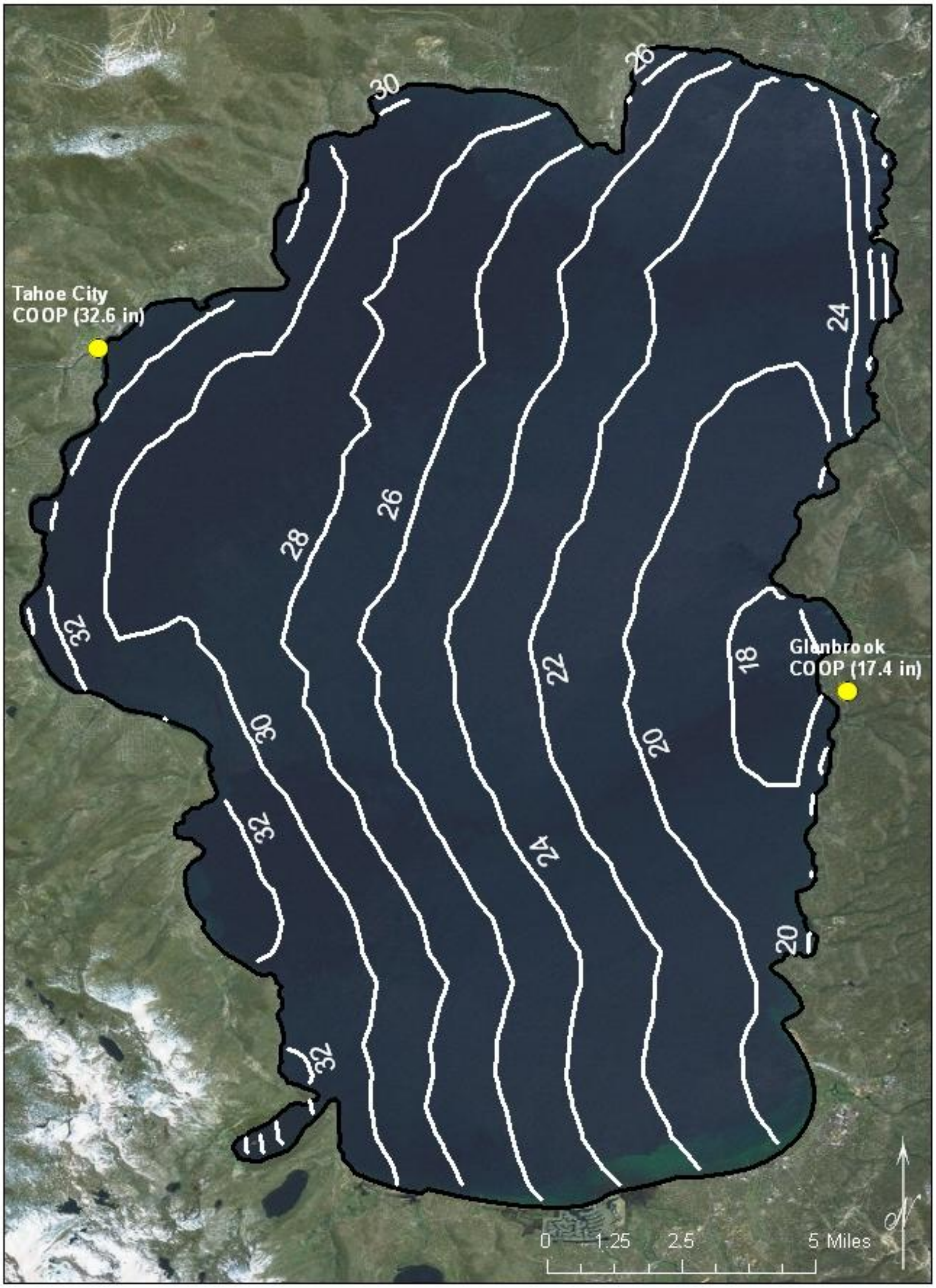


Figure 11.  Mean annual 1971-2000 PRISM precipitation contours for Lake Tahoe.

Table 9. Mean monthly PRISM precipitation fractions for each water body and respective weather station.

| **Fraction of 1971-2000 PRISM Spatially Averaged Water Body Precipitation to 1971-2000 Weather Station Precipitation** | **Jan** | **Feb** | **Mar** | **Apr** | **May** | **Jun** | **Jul** | **Aug** | **Sep** | **Oct** | **Nov** | **Dec** | **Ann** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Boca PRISM / Boca COOP | 1.06 | 1.01 | 1.16 | 1.01 | 0.96 | 0.85 | 0.76 | 0.88 | 0.99 | 1.10 | 1.02 | 1.01 | 0.98 |
| Martis PRISM / Truckee Ranger COOP | 0.96 | 0.89 | 1.00 | 0.81 | 0.97 | 0.99 | 0.92 | 0.84 | 1.07 | 1.01 | 0.94 | 0.92 | 0.94 |
| Prosser PRISM / Boca COOP | 1.43 | 1.33 | 1.48 | 1.33 | 1.14 | 0.95 | 0.67 | 0.88 | 1.09 | 1.25 | 1.33 | 1.28 | 1.18 |
| Stampede PRISM / Boca COOP | 1.41 | 1.43 | 1.61 | 1.38 | 1.19 | 0.90 | 0.74 | 0.92 | 1.11 | 1.37 | 1.42 | 1.32 | 1.23 |
| Independence PRISM / Boca COOP | 1.89 | 1.86 | 2.25 | 2.29 | 1.86 | 1.33 | 0.78 | 1.02 | 1.37 | 1.68 | 1.88 | 1.82 | 1.67 |
| Donner PRISM / Donner COOP | 0.99 | 0.91 | 1.07 | 0.94 | 1.05 | 0.96 | 1.05 | 0.97 | 1.13 | 1.07 | 0.97 | 0.97 | 1.01 |
| Donner PRISM /Boca COOP | 1.88 | 1.83 | 2.10 | 2.03 | 1.53 | 1.19 | 0.83 | 1.02 | 1.28 | 1.72 | 1.81 | 1.72 | 1.58 |
| Donner PRISM / Tahoe City COOP | 1.16 | 1.13 | 1.39 | 1.21 | 1.35 | 1.03 | 1.31 | 1.23 | 1.31 | 1.22 | 1.17 | 1.13 | 1.22 |
| Tahoe PRISM / Tahoe City COOP | 0.75 | 0.73 | 0.83 | 0.67 | 0.80 | 0.84 | 0.88 | 0.92 | 0.90 | 0.80 | 0.74 | 0.74 | 0.80 |
| Lahontan PRISM / Lahontan Dam COOP | 0.99 | 0.96 | 1.04 | 0.97 | 1.07 | 1.07 | 0.80 | 1.02 | 1.05 | 1.10 | 0.95 | 1.13 | 1.01 |

The application of this scaling procedure is most appropriate for monthly periods; however, without observed daily precipitation records at the water bodies of interest, this approach of scaling may be reasonably extended to estimating daily precipitation for operational and accounting requirements. For example, the closest precipitation gage to Stampede reservoir is located at Boca reservoir, which is at a lower elevation than Stampede. To estimate daily precipitation at Stampede, the Stampede/Boca fraction of the spatially-averaged mean-monthly $PRISM\ PPT_{month\ i}$ would be multiplied by the Boca COOP station recorded daily precipitation for *month i*. Because Stampede is at a higher elevation than the weather station, the fraction for any given month should be greater than 1 because precipitation and elevation are positively correlated in the region. As shown in Table 9, the annual fraction of Stampede PRISM / Boca COOP precipitation is 1.23. However, for summer months (June, July, August), the monthly Stampede PRISM / Boca COOP station precipitation fractions are less than one (0.90, 0.74, 0.92, respectively). This trend seems to be consistent, even for monthly fractions where the weather station is located near the water body (i.e., Boca PRISM / Boca COOP). Caution should be used when estimating summer precipitation using a precipitation station that is distant from the water body of interest, as this approach is highly uncertain due the convective and localized nature of summer storms.

For this work, the goal was to revise long-term mean monthly net-evaporation estimates used in current USBR operations (Table 10). To accomplish this goal with limited historical weather data, evaporation was estimated using the CRLE model for a 10-year period from 2000 to 2009, while 1971 to 2000 PRISM precipitation was used to compute mean monthly net evaporation. The mismatch in mean monthly periods between CRLE modeled evaporation (2000 to 2009) and PRISM precipitation (1971 to 2000) is due to the limited availability of quality weather data (specifically $R_s$, $T_a$, and $T_{dew}$) for CRLE model input, and to a lesser extent, limited availability of long-term PRISM precipitation data (i.e., greater than a 30-year period) at a spatial resolution required (less than 800 m) to accurately estimate precipitation over small water bodies.

Results of CRLE modeled evaporation suggest that yearly and decadal variability in modeled evaporation is very small from 2000 to 2009, while variability in observed precipitation is large over the same period. In developing congruent evaporation and precipitation "monthly normals" to estimate net evaporation, it was assumed that the 10-year (2000 to 2009) mean-monthly CRLE-modeled evaporation is representative of long-term monthly normals and can be paired to 30-year (1971 to 2000) monthly PRISM precipitation normals, to compute long-term (quasi 30-year) monthly normals of net evaporation. Table 11 lists the estimated mean monthly net evaporation for each water body, computed as the difference between mean monthly evaporation (adjusted for ice cover) and PRISM precipitation (Tables 7 and 8). Net evaporation is often negative in the winter months, where there is more precipitation than evaporation. Mean annual net evaporation estimates range from 44 inches for Lahontan reservoir, to 0.3 inches for Independence Lake. The extreme range is related to the distribution of precipitation. Lahontan reservoir receives on average

5.6 inches of precipitation, while Independence Lake receives on average 41.2 inches of precipitation according to the 1971 to 2000 PRISM precipitation distribution. Figure 12 illustrates the monthly distribution of net evaporation for each water body.

Table 10. Scanned table of Boca pan evaporation estimates (obtained from the Federal Water Master's Office) currently used for reservoir operations.

STAMPEDE RESERVOIR
AVERAGE NET EVAPORATION LOSS

| | A | B | C | | D | E | F | | G | H |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | (A*B) | | | (D*1.136) | (E*.75) | | (C-F) | |
| | AVG PAN EVAP. | PAN FACTOR | RESERVOIR EVAP. | | BOCA AVG. PRECIP | STAMP. AVG. PRECIP | PRECIPITATION GAIN | | NET EVAP. LOSS | ADJUSTED NET EVAP. LOSS |
| | (IN) | | (IN) | (FT) | (IN) | (IN) | (IN) | (FT) | (FT) | (FT) |
| JAN | 1.5 | 1.0 | 1.5 | .12 | 4.34 | 4.93 | 3.70 | .31 | -.19 | 0 |
| FEB | 2.0 | .9 | 1.8 | .15 | 2.98 | 3.39 | 2.54 | .21 | -.06 | 0 |
| MAR | 4.0 | .8 | 3.2 | .27 | 2.49 | 2.83 | 2.12 | .18 | .09 | .08 |
| APR | 4.9 | .74 | 3.6 | .30 | 1.41 | 1.60 | 1.20 | .10 | .20 | .17 |
| MAY | 7.1 | .74 | 5.3 | .44 | 1.22 | 1.39 | 1.04 | .09 | .35 | .30 |
| JUNE | 8.6 | .74 | 6.4 | .53 | .69 | .78 | .59 | .05 | .48 | .41 |
| JULY | 10.2 | .74 | 7.5 | .63 | .49 | .56 | .42 | .03 | .60 | .51 |
| AUG | 9.3 | .74 | 6.9 | .57 | .57 | .65 | .49 | .04 | .53 | .46 |
| SEPT | 6.8 | .74 | 5.0 | .42 | .50 | .57 | .43 | .04 | .38 | .33 |
| OCT | 4.3 | .74 | 3.2 | .27 | 1.16 | 1.32 | .99 | .08 | .19 | .16 |
| NOV | 2.0 | .9 | 1.8 | .15 | 2.09 | 2.37 | 1.78 | .15 | 0 | 0 |
| DEC | 1.5 | 1.0 | 1.5 | .12 | 3.78 | 4.29 | 3.22 | .27 | -.15 | 0 |
| ANNUAL | 62.2 | .767 | 47.7 | 3.97 | 21.72 | 24.68 | 18.52 | 1.55 | 2.42 | 2.42 |

A - Evaporation rate at Stampede was estimated to be the same as at Boca Reservoir (see attached table).
B - See note for column A.
C - See note for column A.
D - NOAA, Climatological data, 1984 California Annual Summary.
E - Stampede estimated normal annual precipitation (25 inches) / Boca normal annual precipitation (22 inches) = 1.136.
F - Precipitation gain due to having precipitation fall directly on the reservoir surface is the amount of precipitation that would not have contributed to gaged flow under pre-reservoir conditions. Precipitation that would have contributed to gaged flow under pre-reservoir conditions must be made available to meet prior downstream rights. Precipitation gain is estimated to be 75% of the total precipitation.
G - Net loss of Little Truckee River flow due to Stampede Reservoir evaporation.
H - Net gain of .40 feet in December-February was redistributed to March-October and used to reduce net losses in these months by multiplying by the ratio 2.42/2.82. This adjustment will help to avoid having a situation where the actual inflow including precipitation on the reservoir surface is insufficient to meet the indicated average gain.

Table 11. Mean monthly net evaporation for each water body computed as the difference between mean monthly evaporation (adjusted for ice cover) and precipitation (Tables 7 and 8).

| Water Body | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | Ann |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Boca** | -3.6 | -3.6 | -2.5 | 0.6 | 2.3 | 4.2 | 6.2 | 6.7 | 5.6 | 4.1 | 1.1 | -1.2 | 19.9 |
| **Martis** | -5.1 | -4.9 | -3.5 | 1.1 | 3.5 | 5.6 | 7.2 | 6.8 | 5.0 | 2.6 | -1.2 | -3.4 | 13.6 |
| **Prosser** | -5.2 | -4.8 | -3.8 | 0.1 | 2.0 | 4.1 | 6.2 | 6.7 | 5.5 | 3.9 | 0.3 | -2.2 | 12.9 |
| **Stampede** | -3.5 | -5.0 | -3.7 | 0.0 | 1.8 | 3.9 | 5.9 | 6.5 | 5.5 | 3.8 | 0.3 | -1.2 | 14.3 |
| **Independence** | -6.5 | -6.8 | -6.2 | -2.2 | 0.6 | 3.6 | 6.0 | 6.6 | 5.5 | 3.5 | -0.9 | -2.9 | 0.3 |
| **Donner** | -4.7 | -5.9 | -4.8 | -0.9 | 1.1 | 3.3 | 5.4 | 6.2 | 5.5 | 3.6 | -0.5 | -2.1 | 6.2 |
| **Tahoe** | -1.0 | -2.2 | -1.9 | 0.1 | 1.1 | 2.4 | 4.4 | 5.4 | 5.3 | 4.5 | 2.0 | 1.1 | 21.0 |
| **Lahontan** | 0.7 | 0.4 | 0.8 | 2.0 | 3.6 | 5.4 | 7.6 | 7.7 | 6.3 | 5.1 | 3.0 | 1.7 | 44.4 |

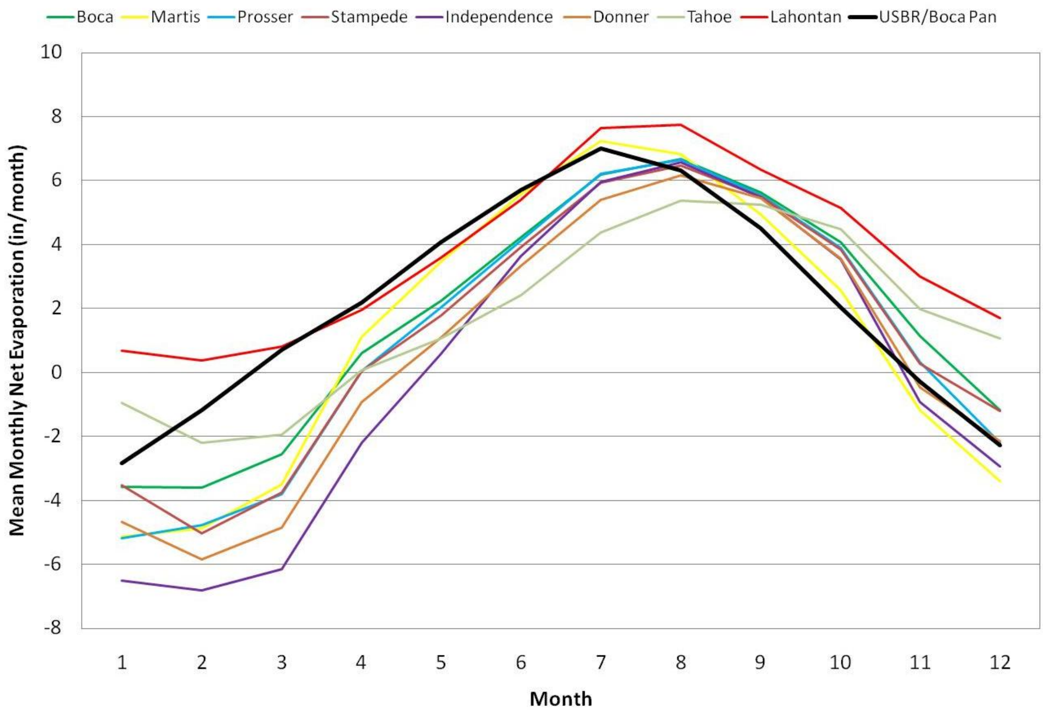


Figure 12. Mean monthly net evaporation for each water body computed as the difference between mean monthly evaporation (adjusted for ice cover) and precipitation (Tables 7 and 8).

## Validation

An important component in any modeling study is evaluation of model accuracy. Morton (*1986*) compared CRLE model evaporation to water balance evaporation estimates from many lakes in Nevada, Utah, and California, including Pyramid Lake, NV; Lake Winnemucca, NV; Walker Lake, NV; Utah Lake, UT; Great Salt Lake, UT; Tulare Lake, CA; Silver Lake, CA; Elsinore Lake, CA; Buena Vista Lake, CA; and Salton Sea, CA. While these comparisons by Morton (*1986*) were extremely valuable, more recent comparisons were desired; therefore, recent water balance, energy balance, and aerodynamic estimates of lake evaporation in Nevada and California were computed and obtained, and compared to CRLE-modeled evaporation for respective water bodies and time periods. Details of the weather data and processing procedures for CRLE validation is described below.

In comparing Walker Lake CRLE-modeled evaporation to U.S. Geological Survey (USGS) Bowen ratio evaporation estimates from 2005 to 2007 (*Allander et al., 2009*), measured $R_s$ and $T_a$ at the Dead Camel Mountain RAWS station, 40 miles northwest of Walker Lake was assumed to be representative of conditions at Walker Lake. $T_{dew}$ was derived from over-water measurements made on the USGS Bowen ratio platform (*Allander et al., 2009*) and used for CRLE input. To address potential uncertainties in the Bowen ratio approach, Lopes and Allander (*2009*) re-estimated evaporation for Walker Lake from 1988 to 1994 using a water balance approach. CRLE input data was developed for Walker Lake for water years 1993 and 1994 using $T_a$ measurements, and estimates of $R_s$ and $T_{dew}$ from the Hawthorne COOP weather station made in Huntington and Allen (*2010*). CRLE-modeled evaporation was then compared to Walker Lake water budget estimates for water years 1993 and 1994. A comparison for the full period reported by Lopes and Allander (*2009*) (i.e., 1988 to 1994) was not made due to missing weather data at the Hawthorne COOP weather station.

For Pyramid Lake CRLE input, measured $R_s$, $T_a$, and $T_{dew}$ were derived from near-shore USGS weather stations operated from 1987 to 1989 (*Hostetler and Benson, 1993*). CRLE-modeled evaporation was then compared to evaporation derived using an aerodynamic approach from 1987 to 1989 (*Benson and White, 1994*). For Lake Tahoe CRLE comparisons, an average of published results from several evaporation approaches outlined by Trask (*2007*) (pan, water budget, energy balance, mass transfer) were compared to the 10 year (2000 to 2009) average CRLE evaporation estimates using $R_s$, $T_a$, and $T_{dew}$ collected at the USCG pier weather station. In addition, CRLE evaporation was compared to a bulk aerodynamic-mass transfer evaporation estimate for 2004 following the approach outlined by Allen and Tasumi (*2005*) and Kondo (*1975; 1994*), using NASA Lake Tahoe buoy data.

Results of CRLE-modeled evaporation for water bodies were paired with previously published estimates described above and are shown in Figure 13 and Table 12. These previous evaporation estimates include those reported from Allander et al. (*2009*), Lopes and Allander (*2009*), Trask (*2007*), Benson and White (*1994*), Morton (*1986*), Hostetler and Benson (*1993*), Myrup et al. (*1979*), Dugan and McGauhey (*1974*), Harding (*1962*), Hughes (*1967*), Harbeck et al. (*1958*), Blaney (*1957*), Langbein (*1951*), and Harding (*1935*). As shown in Figure 13, annual CRLE evaporation estimates are almost entirely within ±10% of the 1:1 line with independent evaporation estimates. These results highlight the CRLE model's ability to predict annual evaporation using limited weather data. However, Lake Tahoe CRLE estimates have a positive bias beyond +10% of the 1:1 line when compared to the NASA-buoy derived bulk aerodynamic-mass transfer estimate for 2004, precipitation de-correlation water budget, and combination (pan, energy balance, mass transfer) estimates from Trask (*2007*) (Figure 13). There could be several reasons for the bias, including (1) the fact that NASA buoy-measured wind speed and relative humidity (the two most sensitive variables in the bulk mass transfer-aerodynamic method) were extremely variable when all four buoys were compared, and data had to be combined and averaged to make a complete data set for 2004; (2) the mismatch in the period of record for comparison being 1968 to 2000 for Trask's (*2007*) estimate, and 2000 to 2009 for the CRLE estimate; or (3) CRLE model processes could be too simple represent the complex nature of heat storage and evaporation that occurs at Lake Tahoe.

Figure 14 illustrates mean monthly evaporation for several different methods for Lake Tahoe, where it can be seen that the CRLE captures the general seasonality in evaporation when compared to other methods; however, it estimates the highest evaporation overall. It should be noted that Trask (*2007*) reports a ± 20% uncertainty in the Adams vector mass transfer approach (*Adams et al., 1990*) shown in Figure 14. Without a direct way to measure evaporation, and with a limited number of studies that have been conducted to estimate evaporation, it is difficult to know what method or estimate is most accurate, however there does seem to be consistency in previous evaporation estimates for Lake Tahoe, some of which fall within ±10% of the 1:1 line of the CRLE estimates.

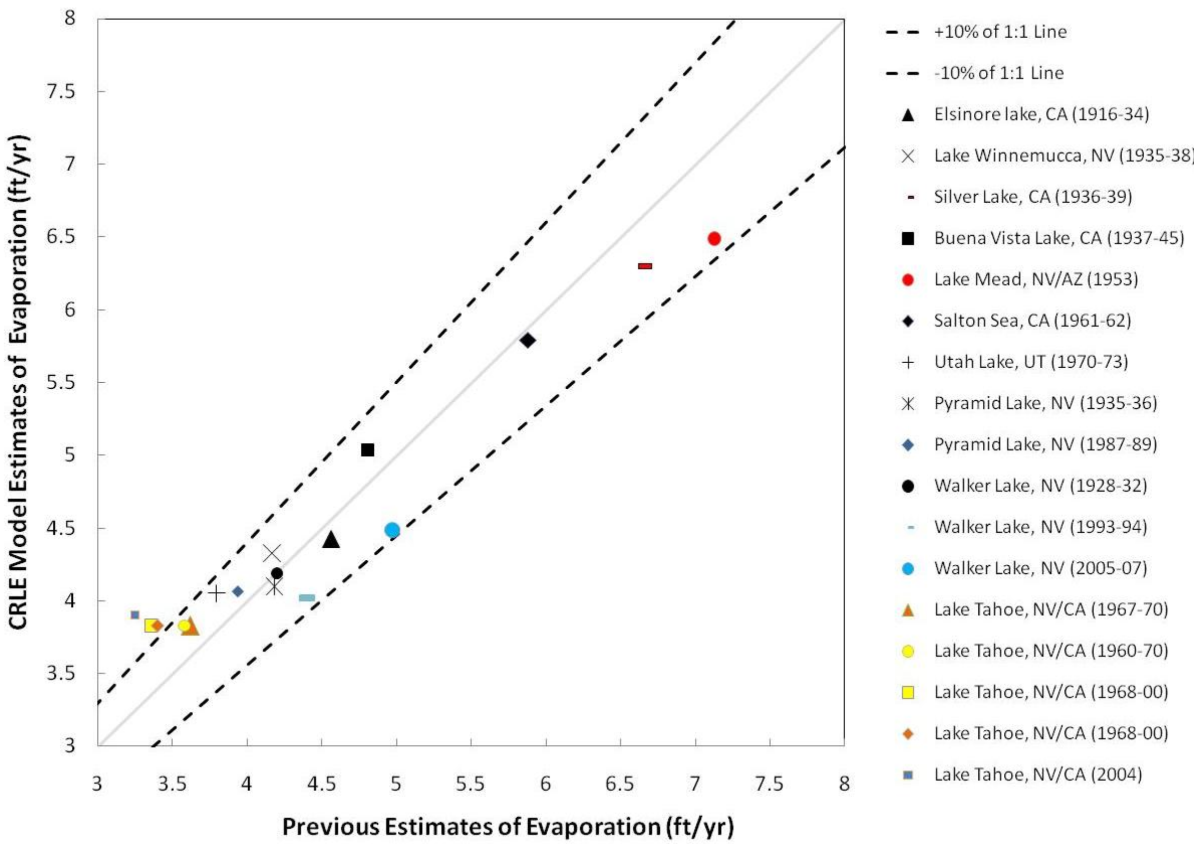


Figure 13. Results of CRLE modeled evaporation compared with previously published estimates.

## Limitations of Methodology

The methods for estimating open water evaporation applied in this report are not absent of uncertainties and limitations. Uncertainties and limitations with evaporation estimates are a result of errors in model structure, inaccuracies in instrumentation used to collect meteorological data, or inaccuracies in estimating weather variables where they are not measured, such as dew point and solar radiation as done in this work. Winter (*1981*) concluded that accuracy of energy balance errors are generally about ±10%, but Morton (*1986*) argued that errors in the energy balance approach are likely far greater than ±10%, due to uncertainties in net radiation, heat storage, and spatial variability of measured energy fluxes. For example, it has been found that high-performance net radiometer readings can have uncertainties of 10% to 26% for field or factory calibration, respectively (*Michel et al., 2007*).

Table 12. Results of CRLE modeled evaporation compared with previously published estimates.

| Water Body | CRLE Modeled Evaporation (ft/yr) | Previous Evaporation Estimate (ft/yr) | Type | Previous Estimate Source | Notes |
|---|---|---|---|---|---|
| Lake Winnemucca, NV (1935-38) | 4.33 | 4.16 | Water Budget | Harding (1962) | From Morton (1986) |
| Pyramid Lake, NV (1935-36) | 4.10 | 4.18 | Water Budget | Harding (1962) | From Morton (1986) |
| Walker Lake, NV (1928-32) | 4.19 | 4.20 | Water Budget | Harding (1935) | From Morton (1986) |
| Utah Lake, UT (1970-73) | 4.05 | 3.80 | Water Budget | Fuhriman et al. (1981) | From Morton (1986) |
| Great Salt Lake, UT (1919-34) | 3.30 | 3.32 | Water Budget | Langbein (1951) | From Morton (1986) |
| Silver Lake, CA (1936-39) | 6.30 | 6.62 | Water Budget | Blaney (1957) | From Morton (1986) |
| Salton Sea, CA (1961-62) | 5.79 | 5.88 | Water Budget | Hughes (1967) | From Morton (1986) |
| Buena Vista Lake, CA (1937-45) | 5.04 | 4.81 | Water Budget | Langbein (1951) | From Morton (1986) |
| Elsinore lake, CA (1916-34) | 4.42 | 4.56 | Water Budget | Harding (1935) | From Morton (1986) |
| Lake Mead, NV/AZ (1953) | 6.49 | 7.13 | Water Budget & Mass Transfer | Harbeck (1958) | Water year average of 7.09ft and 7.15ft of energy. Balance and mass transfer methods, respectively |
| Pyramid Lake, NV (1987-89) | 4.06 | 3.94 | Mass Transfer | Benson and White (1994) | From S. Hostetler (unpublished) |
| Walker Lake, NV (2005-07) | 4.49 | 4.97 | Energy Balance Bowen Ratio | Allander et al. (2009) | Advected energy from inflow of 47mm (3.7w/m2) was added to CRLE estimate |
| Walker Lake, NV (1993-94) | 4.02 | 4.35 | Water Budget | Lopes and Allander (2009) | Used mean of water years 1993-1994 water budget evaporation estimates of 4.35ft/yr, and mean of waters 1993-1994 CRLE estimates of 4.02 ft/yr using the Hawthrone COOP weather station. Lopes and Allander's mean annual estimate from 1988-1994 was 4.3 ft/yr |

Table 12. Results of CRLE modeled evaporation compared with previously published estimates (continued).

| Water Body | CRLE Modeled Evaporation (ft/yr) | Previous Evaporation Estimate (ft/yr) | Type | Previous Estimate Source | Notes |
|---|---|---|---|---|---|
| Lake Tahoe, NV/CA (1967-70) | 3.83 | 3.62 | Water Budget | Myrup et al. (1979) | Used water balance data from 1967-1970, paired to the 2000-2009 mean annual CRLE estimate |
| Lake Tahoe, NV/CA (1960-70) | 3.83 | 3.58 | Water Budget | Dugan and McGauhey (1974) | Used water balance data from 1960-1970, paired to the 2000-2009 mean annual CRLE estimate |
| Lake Tahoe, NV/CA (1968-00) | 3.83 | 3.36 | Water Budget | Trask (2007) | Used Trask's precipitation decorrelation water budget mean evaporation estimate + 9.3% reported uncertainty, paired to the 2000-2009 mean annual CRLE estimate |
| Lake Tahoe, NV/CA (1968-00) | 3.83 | 3.40 | Combination of Pan, Energy Budget, Mass Transfer | Trask (2007) | Used Trask's combined mean evaporation estimate + 11.6% reported uncertainty, paired to the 2000-2009 mean annual CRLE estimate |
| Lake Tahoe, NV/CA (2004) | 3.90 | 3.25 | Bulk Aerodyanmic - Mass Transfer | Huntington and McEvoy (2011), this report | Used NASA buoy data for 2004 for the bulk-aerodynamic mass transfer estimate, and 2004 USGC pier weather data for the CRLE estimate |

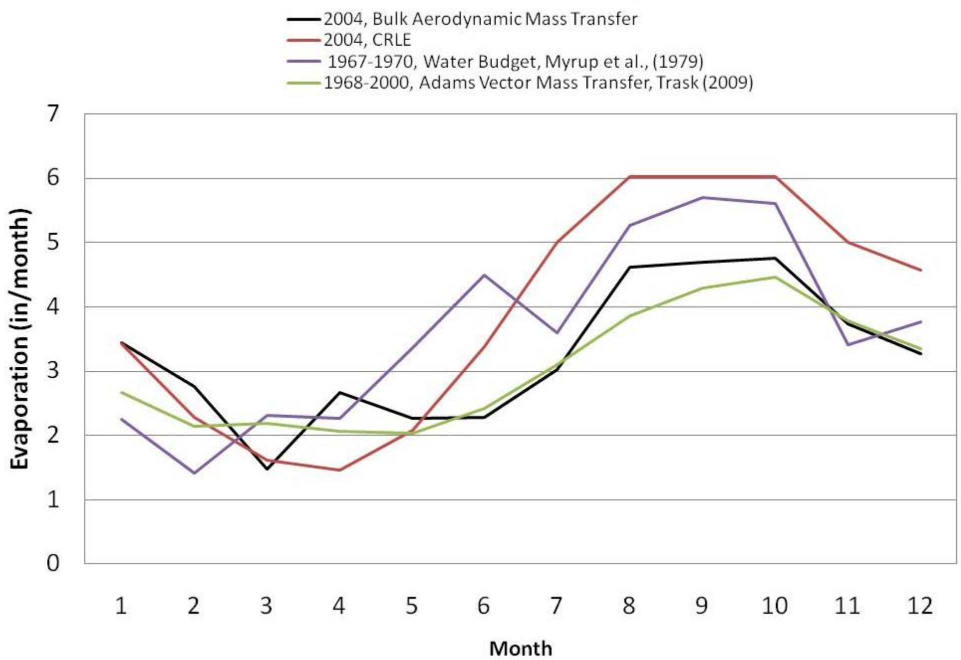

Figure 14. Mean monthly evaporation for several different methods for Lake Tahoe.

Morton (*1994*) argues that the water balance approach is the closest to a "measurement" of evaporation that exists, and used water budget evaporation estimates to calibrate and validate the CRLE. The conceptual basis for the heat-storage routing technique in the CRLE, based on water body depth, is grossly oversimplified. In spite of the weakness of the routing technique it is "worthwhile because it has the potential to provide reasonably realistic seasonal patterns of evaporation for many lakes and to account for the effects of great depth in reducing the annual lake evaporation" (*Morton, 1986*). Moreover, more complex improvements are not warranted until accurate energy or water-budget bench mark datasets of monthly evaporation can be developed so that further development and calibration of a more robust approach can be implemented.

One of the major limitations of the CRLE model is that it does not take into account the effects of wind speed on evaporation. Conversely, it is argued that using a method that relies on wind speed (e.g., the aerodynamic-mass transfer or combination approach), may actually increase the uncertainty in evaporation estimates, especially if wind speed is measured over land, or estimated from a distant site. This is an important point because almost all alternative approaches are extremely sensitive to wind speed. While there are several limitations to the CRLE approach, most seem minor compared to the difficulties, limitations, and data needs required in other open-water evaporation approaches. In comparing the CRLE to previous estimates of evaporation, as done in this work, it seems that the CRLE performs well and is stable given the uncertainties in input data, model structure, and assumptions. To further validate its use, additional research on open-water evaporation in the area is needed.

## CONCLUSIONS

Monthly evaporation and net evaporation estimates are required for reservoir operations and the development of new storage and water-accounting strategies. Historically, evaporation from lakes and reservoirs has been estimated using pan evaporation information, which is widely known to have significant uncertainty both in magnitude and timing. Currently, evaporation estimates for lakes and reservoirs in the Truckee-Carson basins are based on pan evaporation data. The objective of this study was to estimate mean monthly and mean annual open-water net evaporation from lakes and reservoirs in the Truckee-Carson basins using available land-based weather data with a widely accepted approach that is relatively accurate on both a seasonal and annual basis. Evaporation estimates were made for Stampede, Boca, Prosser, Martis, and Lahontan reservoirs; and Lake Tahoe, Donner Lake, and Independence Lake. The approach chosen for estimating monthly and annual evaporation is based on complementary theory, and termed the Complementary Relationship Lake Evaporation (CRLE) model. The advantage of this model is that it only requires monthly air temperature, dew point, and solar radiation data, making it ideal for this study because weather data required for more complex approaches simply did not exist at water bodies of interest. Another advantage of the CRLE model is that it simulates the impact of heat storage on the time lag of evaporation. The CRLE model proved extremely useful in accurately simulating the offset in peak evaporation due to heat storage, as many local studies have shown.

Estimates of mean monthly evaporation were made from 2000 to 2009 using the CRLE model and adjusted due to ice cover using Landsat TM imagery. Mean monthly net evaporation (i.e., ice cover adjusted monthly evaporation – precipitation) was then estimated using PRISM mean monthly precipitation data. A validation of CRLE was performed by compiling 10 previously published validation points, and conducting eight new validation points for lakes and reservoirs in Nevada, Arizona, California, and Utah. Results of the validation suggest that the CRLE model is fairly robust for predicting annual evaporation, and simulates reasonably accurately the seasonal trend in evaporation as estimated by water and energy budgets, and aerodynamic approaches. While the CRLE model does have limitations, at this time it is believed to be the most appropriate approach to estimate evaporation given current data availability. To improve annual and seasonal evaporation estimates from water bodies of interest, a reservoir-based meteorological network needs to be implemented to collect data required for more complex and more accurate approaches. These additional data could also be used to further test and validate the evaporation estimates made in this report.

## REFERENCES


Adams, E.E., Cosler, D.J., and Helfrich, K.R. (1990). Evaporation from Heated Water Bodies: Predicting Combined Forced Plus Free Convection. *Water Resources Research*, 36(3):425-435.

Allen, R.G. (1996). Assessing Integrity of Weather Data for use in Reference Evapotranspiration estimation. *Journal of Irrigation and Drainage Engineering*, ASCE, 122(2):97-106.

Allen, R.G. and Tasumi, M. (2005). Evaporation from American Falls Reservoir in Idaho via a Combination of Bowen Ratio and Eddy Covariance. Proceedings 2005 EWRI Conf., Anchorage, Alaska, May 15-19.

Allander, K.K., Smith, J.L., and Johnson, M.J. (2009). Evapotranspiration in the Lower Walker River Basin, West-Central Nevada, Water Years 2005-07. *U.S. Geological Survey Scientific Investigations Report 2009-5079*, 62 p.

ASCE-EWRI. (2005). The ASCE Standardized Reference Evapotranspiration Equation. ASCE-EWRI Standardization of Reference Evapotranspiration Task Committee Report, available at http://www.kimberly.uidaho.edu/water/asceewri/

Benson, L.V. and White, J.W.C. (1994). Stable isotopes of oxygen and hydrogen in the Truckee River-Pyramid lake surface-water system. 3. Source of water vapor overlying Pyramid Lake. *Limnol. Oceanogr.*, 39(8):1945-1958.

Blaney, H.F. (1957). Evaporation study at Silver Lake in the Mojave Desert, California. *Eos Trans. AGU*, 38(2):209-215.

Brutsaert, W.H. and Yeh, G.-T. (1976). Implications of a type of empirical evaporation formula for lakes and pans, *Water Resources Research*, 6:1202-1208.

Brutsaert, W. and Stricker, H. (1979). An advection-aridity approach to estimate actual regional evapotranspiration, *Water Resources Research.*, 15:443-450.

Crago, R.D., Qualls, R.J., and Feller, M. (2010). A calibrated advection-aridity evaporation model requiring no humidity data. *Water Resources Research*, 46, W09519, doi:10.1029/2009WR008497

Daly, C., Neilson, R.P., and Phillips, D.L. (1994). A statistical-topographic model for mapping climatological precipitation over mountainous terrain. *Journal of Applied Meteorology*. 33:140-158.

Derecki, J.A. (1981). Operational Estimates of Lake Superior Evaporation Based on IFYGL Findings. *Water Resources Research*, 17(5):1453-1462.

Dillon, T.M. and Powell, T.M. (1976). Low-Frequency Turbulence Spectra in the Mixed Layer of Lake Tahoe, California-Nevada. *Journal of Geophysical Research* 81(36): 6421-6427.

DosReis, R.J. and Dias, N.L. (1998). Multi-season lake evaporation- energy budget estimates and CRLEmodel assessment with limited meteorological observations. *Journal of Hydrology*, 208:135-147.

Dugan, G.L. and McGauhey, P.H. (1974). Enrichment of Surface Waters. Journal WPCF, 46(10).

Harbeck, G.E., Jr., et al. (1958). Water loss investigations: Lake Mead studies, *U.S. Geological Survey Professional Paper 298*.

Harbeck, E.G. (1962). A Practical Field Technique for Measuring Reservoir Evaporation Utilizing Mass-Transfer Theory. *U.S. Geological Survey Professional Paper #272-E*.

Harding, S.T. (1935). Evaporation from large water surfaces based on records in California and Nevada. *Eos. Trans. AGU*, 17, 507-511.

Harding, S.T. (1962). Evaporation from Pyramid and Winnemucca lakes, Nevada. *Journal of Irrigation and Drainage*, Division of the American Society of Civil Engineers, 88(IRI), 1-13.

Hobbins, M.T., Ramirez, J.A., and Brown, T.C. (2001). The complementary relationship in estimation of regional evapotranspiration: an enhanced Advection–Aridity model. *Water Resources Research*, 37(5):1389–1403.

Hounam, C.E. (1973). Comparison between pan and lake evaporation, *World Meteorological Organization, Technical Note No. 126*, 52p.

Hostetler, S.W. and Benson, L.V. (1993). Meteorological and water temperature data for Pyramid Lake, Nevada, 1987-89. *U.S. Geological Survey, Open-file Report 92-159*.

Hughes, G.H. (1967). Analysis of techniques used to measure evaporation from Salton Sea, California. *Prof. Paper 272-H, U.S. Geological Survey*, Washington, DC.

Huntington, J.L and Allen, R. (2010). Evapotranspiration and Net Irrigation Water Requirements for Nevada. *Nevada State Engineer's Office Publication*, 266 pp.

Huntington, J.L., Szilagyi, J., Tyler, S.W., and Pohll, G.M. (2011). Evaluating the complementary relationship for estimating evapotranspiration from arid shrublands, *Water Resources Research*, doi:10.1029/2010WR009874.

Jones, R.N., McMahon, T.A., and Bowler, J.M. (2001). Modelling historical lake levels and recent climate change at three closed lakes, Western Victoria, Australia (c. 840-1990). *Journal of Hydrology*, 246:159-180.

Kahler, D.M. and Brutsaert, W. (2006). Complementary relationship between daily evaporation in the environment and pan evaporation. *Water Resources Research, 42,* W05413, doi:10.1029/2005WR00454.

Kohler, M.A., Nordenson, T.J., and Baker, D.R. (1959). Evaporation Maps for the United States. U.S. Dept. of Commerce, Weather Bureau, Technical Paper #37.

Kohler, M.A. and Parmele, L.H. (1967). Generalized estimates of free-water evaporation. *Water Resources Research*, 3:997-1005.

Kondo, J. (1975). Air-Sea Bulk Transfer Coefficients in Diabatic Conditions. *Boundary-Layer Meteorology* 9:91-112.

Kondo, J. (1994). Meteorology in Aquatic Environments, Asakura Publ. Co., Ltd, Tokyo, p.350.

Langbein, W.B. (1951). Research on Evaporation from Lakes and Reservoirs. IASH-AISH Publ. 34, 409-425.

Lopes, T.J. and Allander, K.K. (2009). Water budgets of the Walker River basin and Walker lake, California and Nevada: *U.S. Geological Survey Scientific Investigations Report 2009-5157*, 44p.

Michel, D., Philipona, R., Ruckstuhl, C., Vogt, and Vuilleumier, L. (2007). Performance and Uncertainty of CNR1 Net Radiometers during a One-Year Field Comparison. *Journal of Atmospheric and Oceanic Technology*, 25:442-451.

Morton, F.I. (1979). Climatological estimates of lake evaporation. *Water Resources Research*, 15:64-76.

Morton, F.I. (1983a). Operational estimates of lake evaporation. *Journal of Hydrology*, 66:77-100.

Morton, F.I. (1983b). Operational estimates of areal evapotranspiration and their significance to the science and practice of hydrology. *Journal of Hydrology*, 66:1–76.

Morton, F.I., Fogarasi, S., and Ricard, F. (1985). Operational estimates of areal evapotranspiration and lake evaporation-Program WREVAP. NHRI Paper No. 24, Inland Waters Directorate, Environment Canada, Ottawa, Ont.

Morton, F.I. (1986). Practical Estimates of Lake Evaporation. *Journal of Climate and Applied Meteorology*, 25(3):371-387.

Morton, F.I. (1994). Evaporation research – A critical review and its lessons for the environmental sciences. *Critical Reviews in Environmental Science Technology* 24(3):237-280.

Myrup, L.O., Powell, T.M., Godden, D.A., and Goldman, C.R. (1979). Climatological Estimate of the Average Monthly Energy and Water Budgets of Lake Tahoe, California-Nevada. *Water Resources Research,* 15(6).

Ozdogan, M. and Salvucci, G.D. (2004). Irrigation-induced changes in potential evapotranspiration in southeastern Turkey: Test and application of Bouchet's complementary hypothesis. *Water Resources Research*, 40, W04301, doi:10.1029/2003WR002822.

Penman, H.L. (1948). Natural evaporation from open water, bare soil, and grass, *Proc. Royal Soc. London,* A193:120-146.

Priestley, C.H.B. and Taylor, R.J. (1972). On the assessment of surface heat flux and evaporation using large-scale parameters, *Month. Weather Rev.*, 100:81-92.

Sadek, M.F., Shahin, M.M., and Stigter, C.J. (1997). Evaporation from the Reservoir of the High Aswan Dam, Egypt: A New Comparison of Relevant Methods with Limited Data. *Theory of Applied Climatology*, 56:57-66.

Sellers, W.D. (1965). Physical Climatology. Chicago, The University of Chicago Press, 272 pp.

Szilagyi, J. and Jozsa, J. (2008). New findings about the complementary relationship-based evaporation estimation methods, *Journal of Hydrology*, 354:171–186, doi:10.1016/j.jhydrol.2008.03.008.

Tilzer, M.M. and Goldman, C.R. (1978). Importance of Mixing, Thermal Stratification and Light Adaptation for Phytoplankton Productivity in Lake Tahoe (California-Nevada). *Ecology*, 59(4):810-821.

Trask, J.C. (2007). Resolving Hydrologic Water Balances through Novel Error Analysis with Focus on Inter-annual and long-term Variability in the Tahoe Basin. University of California, Davis, Ph.D. Dissertation. 378 p.

Vallet-Coulomb, C., Legesse, D., Gasse, F., Travi, Y., and Chernet, T. (2001). Lake evaporation estimates in tropical Africa. *Journal of Hydrology*, 245(1-4):1-18.

Winter, T.C. (1981). Uncertainties in estimating the water balance of Lakes: *Water Resources Bulletin*, 17(1):82-115.

Yang, D., Sun, F., Liu, Z., Cong, Z., and Lei, Z. (2006). Interpreting the complementary relationship in non-humid environments based on the Budyko and Penman hypotheses, *Geophys. Res. Lett.*, 33, L18402, doi:18410.11029/12006GL027657.