LAKE EVAPORATION ESTIMATION IN ARID ENVIRONMENTS

FINAL REPORT

by

W.E. Eichinger, J. Nichols, J.H. Prueger, L.E. Hipps, C.M.U. Neale,
D.I. Cooper, and A. S. Bawazir

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W. Eichinger[1], J. Nichols[1], J. Prueger[2], L. Hipps[3], C. Neale[3], D. Cooper[4], and A.S. Bawazir[5]

I. STATEMENT OF THE PROBLEM

Open water evaporation is a currently undetermined loss to the Rio Grande. The Rio Grande provides 97 percent of the water needed in the New Mexico Rio Grande Basin [Hansen, 1996]. As a result of rapid urban and industrial growth, there has been a 35 percent increase in municipal and industrial water use in the corridor from Taos to Las Cruces, NM over the past fifteen years. To compound the problem, it is expected that the water demand in the Rio Grande Valley will more than double over the next fifty years. This growth compounds an existing water problem and adds to the urgency for improved water efficiency and effective long-term planning efforts [Berger, 1997]. Current water management techniques that regulate the flow in the river rely on water budgeting that, in addition to satisfying local needs, must guarantee a certain water level in the river (due to the endangered status of the Rio Grande silvery minnow) and a mandated quantity of water leaving New Mexico (to comply with water agreements with Mexico and Texas). Too little water released from reservoirs results in economic loss downstream and legal action, while too much water released is, from the point of view of New Mexico, essentially wasted.

The existing data on water use are incomplete and often contradictory. Agricultural use accounts for about 80 percent of the surface flow diverted from the Rio Grande (~100,000 acre-feet per year [Hansen and Gould, 1998]), but less than 20 percent of the known losses from the river (most of the diverted water is returned). Water evaporated from open-water surfaces is believed to constitute the major loss from the hydrologic budget of

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the basin. Estimates of evaporative losses range from 230,000 [Hansen and Gould, 1998] to 350,000 [Wilson, 1997] acre feet per year. The evaporative losses from the Elephant Butte Reservoir alone have been estimated to be 140,000 acre-ft per year, with a high of 228,000 acre-ft and a low of 41,000 acre-ft per year [Action Committee of the Middle Rio Grande Water Assembly, 1999]. The wide range of current evaporation estimates makes accurate estimation and forecasting a critical management need. Estimates of losses from seepage into the ground range from 8 to 12 percent of the total losses. If evapotranspiration could be well estimated, it would quantify the open water losses and the bulk of the use by agriculture and riparian vegetative areas (estimated as 136,000 acre-feet per year [Hansen and Gould, 1998]). This hydro-ecological process has been modeled in only a rudimentary way, using fragmented and out-dated quantitative data over the region. Current methods for evaporation estimation (pans, Blaney-Criddle, Penman-Monteith, etc) are not sufficiently accurate to enable precision water planning or to suggest improved management methods. As an example, using the current Bureau of Reclamation model (a modified Penman-Monteith), it is impossible to state definitively whether non-native salt cedar uses more or less water than the native cottonwood trees along extensive reaches of the Rio Grande basin.

The traditional methods of evaporation estimation are not only inaccurate, but do not provide the ability to improve the quality of the evapotranspiration estimates. They lack the physical and biological knowledge that represent the actual environment on the Rio Grande. This preliminary report presents the results of a multi-disciplinary, multi-agency collaborative effort to measure, characterize, and improve modeled open water evaporation from Elephant Butte Reservoir.

The ability to accurately estimate water evapotranspiration is the key element required to make further improvements in water management. The ability to accurately estimate evapotranspiration in the area along the Rio Grande would allow accurate calculation of water use by riparian and agricultural areas (which constitute the majority of the demand for water) as well as open water losses in the Rio Grande basin. This in turn will allow more effective use of available water resources. Further, accurate estimation of the losses provides a basis upon which planning can occur to reduce these losses. Sustainable agriculture in the presence of a rapidly growing water demand depends upon more efficient water use.

II. ELEPHANT BUTTE RESERVOIR

Elephant Butte Reservoir is a large reservoir in the middle Rio Grande Valley that runs north-south through the center of New Mexico. The reservoir itself is roughly 60 km long and 2 to 4 km wide, running north to south, with a total volume of 2.22 million acre-feet of water. This reservoir is surrounded by a semi-arid region with an average annual precipitation between 7 inches and 15 inches over two thirds of the Rio Grande Basin, from San Marcial - Elephant Butte Dam to Radium Springs. Precipitation exceeds 25 inches only where 30 to 75 percent of the annual precipitation is in the form of snow, while in the balance of the watershed snow represents less than 25 percent of the annual precipitation. The vegetation in the area is primarily mature saltcedar that grows in the low lying areas that drain into the lake. The area also includes a limited amount of cottonwood trees, creosote bushes, and mesquite. The Fra Cristobal Mountain Range parallels the eastern and southern part of the reservoir. The western side consists of sediment deposits from the Rio Grande. With a maximum surface area of 36,500 acres, the evaporative losses from the lake are a significant component of the water budget of the region.

The storage content of Elephant Butte Reservoir at the beginning of the year, on December 31, 1999, was 1,708,200 ac-ft at an elevation of 4396.58 feet. The storage content at the end of 2000, was projected to be 1,250,810 at an elevation of 4,380.39 feet. Elephant Butte Reservoir releases for 2000 are estimated to be 801,000 ac-ft.

Figure 1. An overhead photograph of the peninsula upon which the experiment was conducted. The tower and lidars were located at the end (upper right corner). This location put the instruments near the center of the lake with a minimum of interference from dry land.

In order to measure evaporative losses from the reservoir, an instrumented tower was placed at the end of a long, narrow spit of land that extended into the lake (figure 1) (N 33:19.114, W107:10.383). This location allowed placement of the tower in more than 25 ft of water in a central location in the reservoir. The instruments had minimum interference from dry land. The tower was erected in July 2001 and remained in place until April 2002 when the water level in the reservoir dropped to the point where the tower was on dry land. A list of the instruments mounted on the tower is provided in table 1. A listing of the available data is contained in appendix 2.

A. Measurements at Elephant Butte Reservoir. In order to measure the evaporation from Elephant Butte Reservoir, a set of hydrological and meteorological sensors were fielded in 2001 in the north-central portion of the lake. An intensive measurement campaign was conducted from 12 to 24 September 2001. This campaign included the Los Alamos National Laboratory (LANL) scanning Raman lidar, a sodar, as well as high frequency, time series measurements of the instruments on the tower.

Table 1. Instruments Mounted on the Meteorological Tower at Elephant Butte

Instrument	Height Above the Water	Measures
CSAT3, Sonic Anemometer	3.62 m	Wind speed, direction, turbulent quantities
KH20, Krypton Hygrometer	3.62 m	Water vapor concentration fluctuations
HMP45C, Temp-Humidity Probe	2.5 m	Atmospheric temperature and humidity
Q7.1, Net Radiometer	4.50 m	Net long and short wave radiation
MET ONE 34A-L, Cup Anemometer and Vane	5.5 m	Wind direction
Infrared Thermometer	4.5 m	Lake surface temperature
Thermocouple Array	15, 27, 47, 83, 147 cm depths	Lake temperature at various depths

B. Instruments. The instruments shown in figures 2 and 3 comprise an energy/water budget and meteorological flux station. The water/energy budget is composed of measurements of net radiation and heat storage (available energy), and turbulent fluxes of sensible and latent heat, as well as the momentum flux. The available energy is measured by a net radiometer, and a vertical water temperature profile that is used to compute the amount of thermal energy stored in a water column. The sensible, latent heat (evaporation)

Figure 2. The meteorological instrument tower at Elephant Butte and the view to the north-east.

Figure 3. A closeup photograph of the meteorological tower showing the instruments mounted on it.

and momentum fluxes were measured with a sonic anemometer and a fast response hygrometer.

The sonic anemometer measures the three dimensional components of the wind flow (u, v, and w, the three components of the wind speed) at high rates, up to 20 Hz. These wind observations were used to compute the vertical transport term of the eddy covariance fluxes. The krypton hygrometer measures the fluctuations of atmospheric water vapor concentration (q') at the same rate as the sonic anemometer (20 Hz). Together, the fluctuations in the vertical wind speed (w') and water vapor concentration (q') about their mean values were used to calculate the evaporative flux from the lake as $\overline{w' q'}$, where the overbar indicates time averaging. The covariance of these variables is the "standard" reference for flux determination (subject to various corrections for instrument limitations [Webb et al., 1980; Massman, 2000; Massman and Lee, 2002]). This method is accepted as the most physically based technique to measure evaporation and was used in this project as the "truth set". The temperature/humidity probe is used as part of a standard meteorological station that will be used as a data set for evaluating the utility of more advanced models for estimating evaporative flux from the lake.

III. EVAPORATION ESTIMATION

A. Traditional Estimates of Evaporative Fluxes. Over land, the sun deposits its energy in the top few millimeters of the surface. The land surface modulates its temperature so as to partition outgoing energy (sensible and latent heat fluxes, soil heat flux, and outgoing long-wave radiation) in a way that satisfies the physical requirements of the situation. If the surface has vegetation, the system increases in complexity. Depending on the amount of water available, the incoming energy will tend to partition in favor of evaporation. In contrast, over sparsely vegetated arid environments, the partitioning will tend to favor the sensible heat flux. The availability of water near the surface will also govern this partitioning. In general, the energy that drives evaporation comes from and is directly proportional to the available radiation. At night the evaporation rates drop dramatically, although not necessarily to zero, because of heat stored in the ground and from the air itself. At night, a land surface will cool more rapidly than the air, with the result that energy will be extracted from the air to support evaporation. Many of the commonly used, traditional estimates of evaporation (Penman, Penman-Monteith, Priestly-Taylor, etc.) rely on the proportionality between the evaporative flux and the available radiation.

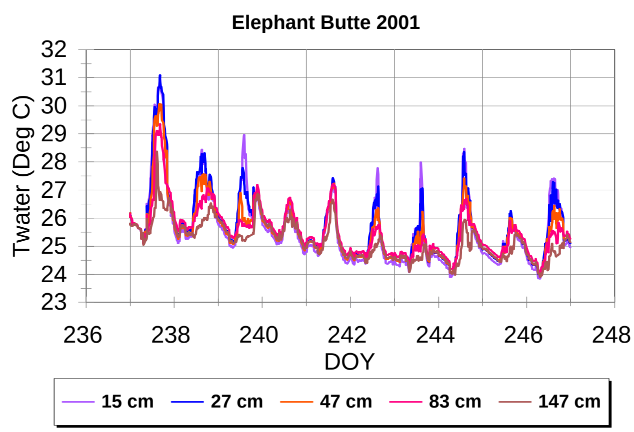

Figure 4. A plot of the temperature at various depths at the tower site in Elephant Butte for a period of ten days following the intensive campaign.

The Penman equation (Eq. 1.) forms the basis for most of the traditional methods

$$LE = \frac{\Delta}{\Delta + \gamma}\left[Rn - G \right] + \frac{\gamma}{\Delta + \gamma} f(\bar{u}) \left[e_{sat} - e_a \right] \quad (1)$$

where $\Delta = de_{sat} / dT$ (the slope of the saturation vapor pressure curve with temperature); γ is the psychometric constant, $\gamma = C_p P / 0.622 L_e$; C_p is the specific heat, at constant pressure, of dry air; P is the atmospheric pressure; L_e is the latent heat of vaporization for water; Rn is the net radiation; G is the storage term; f is an empirical wind function; and $(e_{sat} - e_a)$ is the water vapor pressure deficit in the atmosphere.

Fundamentally, the physics used to derive this semi-empirical model assumes that evaporation is driven by the available energy and the vapor pressure deficit. However, it is well-known that the available energy over water is only weakly related to evaporation (Sellers, 1965). This will be demonstrated later in this section. Further, the empirical wind function is site specific, and is affected by the slope of the terrain and the height and variability of the roughness elements at the surface. In practice, near surface stability also affects the wind function, and but is typically not included in the derivation and handled with empirical "work arounds". In short, substantial errors and uncertainties should be anticipated if this approach is used for estimating open water evaporation.

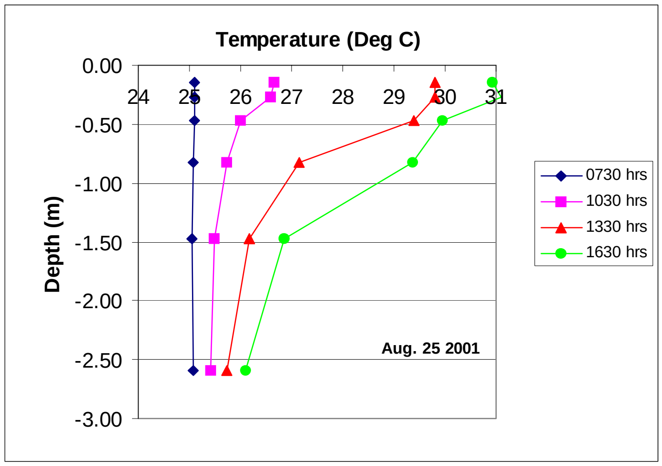

Figure 5. A plot of the temperature at various depths at the tower site in Elephant Butte over the course of a day. Note that the lake temperature below about 1.5 m does not change significantly during the day.

With respect to evaporation, open water bodies are quite different from land surfaces. The sun's energy penetrates the water to depths of as much as 30 m in clear water, somewhat less in turbid water, and is stored throughout the water column. The water column is mixed by surface motion and becomes the source of energy that drives evaporation. Because of the large heat storage capacity of water ($1.006 x 10^6 J/m^3$), and the fact that water is approximately 1000 times more dense than air, the temperature of deep, clear, water bodies does not change significantly throughout the day when compared to the atmosphere (see figure 4 for example). The amount of available energy at the surface is nearly constant throughout the day and night, leading to a nearly constant evaporation rate (figure 6). The water in Elephant Butte Reservoir lies between the two extremes of a clear water body and a land surface. The lake is shallow over much of its area and is relatively turbid, resulting in massive storage of solar energy in a considerably smaller volume. The bulk temperature of the lake (the temperature below about a half meter) will fluctuate to a small degree over the course of a day (figure 5) and the evaporation rate will change with it.

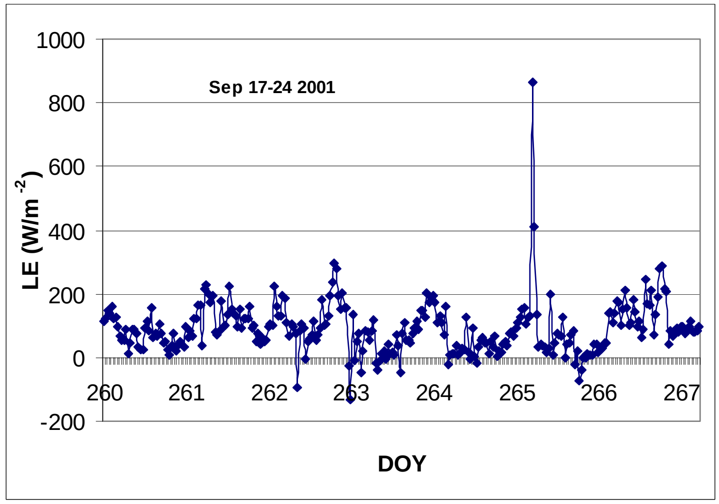

Figure 6. A plot of the evaporation rate over Elephant Butte during the intensive campaign. Note that the rate is essentially constant and does not follow a diurnal cycle (the highs and lows are indicative of changes in wind speed). The one period over 800 W/m^2 occurred during a convective storm.

Methods that use net radiation to estimate evaporation rates must fail, because net radiation is not providing the energy required for evaporation. For example, these models (Eq. 1) will predict a small or zero evaporation rate at night since Rn is small. Over a water body at night, the evaporation rate is in fact, nearly as large as it is during the day. Figure 6 shows the evaporation at the tower during the intensive period. The evaporation rates are nearly constant at approximately 100 W/m^2. The variations observed in Figure 6 are primarily the result of changes in wind speed. Periods of near zero evaporation are actually periods when the winds blow from the north, through the tower before reaching the eddy covariance instruments, and are instrument artifacts in

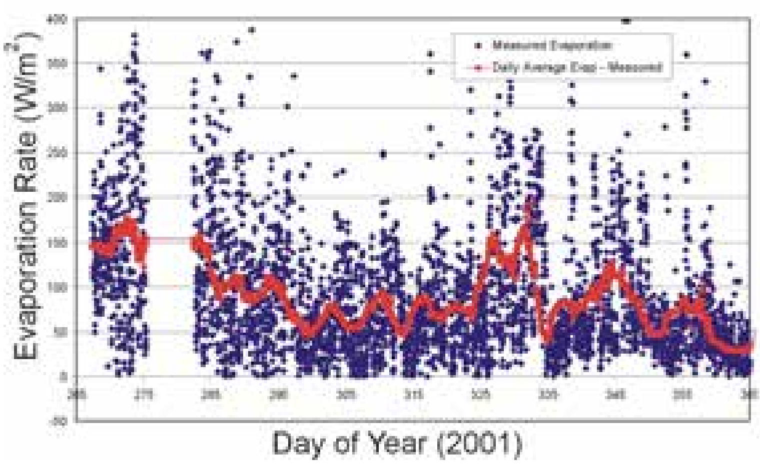

Figure 7. A plot showing the evaporation rate at Elephant Butte during the last quarter of 2001. The red line is a daily running average of the evaporation rate. The high portions of the red line are the result of storms with high winds over the reservoir.

the “truth” set. Even on a daily or weekly basis, conventional methods based on net radiation will not work well. For example, between April and July, the lake temperature will rise significantly as an extremely large amount of energy is stored in the water. Methods that use the net radiation will assume that all of the available energy is going into sensible or latent energy, yet a significant portion is used to warm the lake. On a daily basis, the overestimate of evaporation is not large but is consistently an overestimate, and over a large lake over several months, the amount of error continually accumulates. Similarly, in the fall as the lake cools, these methods will underestimate the evaporation rates. Figure 7 is a plot showing all of the evaporation data collected at the tower during 2001. While the individual evaporation rates are quite scattered, the running average over a 24 hour period is relatively constant. The average over the entire period is 92 W/m^2 (equivalent to 3.26 mm/day). Note that the daily evaporation rate decreases slightly in December. The decrease is associated with westerly winds with smaller velocities (and unusually small momentum fluxes).

An alternative to these traditional methods relies upon the fact that the evaporation rate is known to be proportional to the water vapor deficit above the water surface and to the wind speed (or more precisely, the vertical momentum flux, u_*). While bulk methods using this approach exist, we suggest the use of similarity theory that accounts for atmospheric stability in a more direct way.

B. Monin Obukov Similarity Method Over ideal homogeneous surfaces, Monin-Obukhov Similarity (MOS) Theory relates changes of vertical gradients in wind speed, temperature, and water vapor concentration. According to MOS Similarity Theory, the relationship between the temperature and water vapor concentration at the surface, T_s and q_s, and the wind speed, u(z), temperature, T(z), or water vapor concentration, q(z), at any height, z, within the inner region (first few meters of atmosphere above the surface) of the boundary layer is expressed as

$$u(z) = \frac{u*}{k}\left[\ln\left(\frac{z}{z_0}\right) - \Psi_m\left(\frac{z}{L}\right)\right] \qquad (2a)$$

$$T_s - T(z) = \frac{H}{\rho\ u_*\ k\ C_p}\left[\ln\left(\frac{z}{z_0}\right) - \Psi_h\left(\frac{z}{L}\right)\right] \quad (2b)$$

$$q_s - q(z) = \frac{LE}{\rho\ u_*\ k\ L_e}\left[\ln\left(\frac{z}{z_0}\right) - \Psi_v\left(\frac{z}{L}\right)\right] \quad (2c)$$

Where the Monin-Obukhov length, L, is a stability parameter, defined as:

$$L = \frac{-\rho\ u_*^3}{k\ g\left[\frac{H}{T\ c_p} - 0.61\, LE\right]} \quad (3)$$

z_o is the roughness length (and is assumed to be the same for all variables), H is the sensible heat flux, LE is the latent energy flux, ρ is the density of air, L_e is the latent heat of evaporation for water, c_p is the specific heat for air, k is the von Karman constant (taken at 0.40), u_* is the friction velocity, g is acceleration due to gravity, and Ψ_m, Ψ_h, and Ψ_v are the Monin-Obukhov stability functions for momentum, temperature and water vapor.

Simply, the MOS method assumes that vertical fluxes of scalars and mass are proportional to the difference between values at the surface and some height, z, and scaled by a term that quantifies the turbulent transport, the friction velocity, u*. The method is simple, requiring only a measure of wind speed, temperature and humidity at some height and the temperature at the water surface (the air immediately above the lake surface is assumed to be saturated). At the surface, the wind speed is zero since the kinetic energy of the wind is transferred to the water in the form of waves.

C. Required Instrumentation. Because of the simplicity of the Monin-Obukhov method, no complex instruments are required. Indeed, the instruments needed are little more than a conventional meteorological station. At an appropriate height above the water surface, required measurements are air temperature, humidity, and wind speed. A measurement is also needed of the lake temperature near the surface. This could be done with an infrared thermometer mounted on a mast with the other instruments or with a thermocouple placed near the water surface. Table 2 contains a summary of the suggested instruments. The costs and specifications are typical of precision meteorological instrumentation. At the time of the installation, the surface roughness parameter, z_0, must be computed using data from a sonic anemometer. This needs to be accomplished only once.

The instruments would ideally be placed on a stable platform in the middle of the lake as far from land as possible. It is recognized that because of the depth of the lake and the fact that Elephant Butte Reservoir is a public recreational area, this placement may not be possible. Accurate and reliable evaporation estimates are dependent upon the degree to which the measurements represent the conditions over the lake (and not those of nearby land surfaces). A wide range of alternate locations could prove acceptable, most notably those which are on the downwind side of the lake.

Table 2. Recommended Instruments for Open Water Measurement Sites

Instrument	Measures	Estimated Cost	Standard Uncertainty
Simple Anemometer	Wind speed	$870	±0.2 m/s
Temp-Humidity Probe	Atmospheric temperature and humidity	$800	±0.1°C ± 1% RH
Vane	Wind direction, recommended not required	$200	±0.5°
Infrared Thermometer or Thermocouple in Water	Lake surface temperature	$600	±0.2°C

D. Uncertainty of the Proposed Method Having proposed a specific method to be used for evaporation estimation (Eqs. 2a,b,c and 3), it would be useful to know the accuracy that could be expected from this method. This will be done using a conventional uncertainty analysis [Coleman and Steele, 1989; Taylor, 1982] to estimate the maximum likely uncertainty. The data from the Elephant Butte experiment will be examined to verify the theoretical prediction.

We begin by developing the basic equation defining the evaporation estimate using the proposed method. Combining equations 2a and 2c above and rearranging, one obtains

$$LE = \frac{[\, q_s - q(z)\,]\ \rho\ u(z)\ k^2\ L_e}{\left[\ln\left(\frac{z}{z_0}\right) - \Psi_v\left(\frac{z}{L}\right)\right] * \left[\ln\left(\frac{z}{z_0}\right) - \Psi_m\left(\frac{z}{L}\right)\right]} \qquad (4)$$

where all of the variables are as defined above. To simplify the analysis, the atmosphere is assumed to be neutral, i.e. Ψ_m and Ψ_v the stability corrections functions are zero. This assumption greatly simplifies the analysis without loss of generality. With this assumption, the evaporation estimate becomes

$$LE = \frac{[\, q_s - q(z)\,]\ \rho\ u(z)\ k^2\ L_e}{\left[\ln\left(\frac{z}{z_0}\right)\right]^2} \qquad (5)$$

Using error propagation methods, assuming the measurements are independent (although the relative humidity measurement is not independent of the temperature), and that the fractional uncertainty in air density is equal to the fractional uncertainty in temperature, the fractional uncertainty in the evaporation rates is obtained by summing the contributions in quadrature:

$$\frac{\delta LE}{LE} = \left[\left(\frac{\delta[\, q_s - q(z)\,]}{[\, q_s - q(z)\,]}\right)^2 + \left(\frac{\delta T}{T}\right)^2 + \left(\frac{\delta u(z)}{u(z)}\right)^2 + \left(\frac{\delta \ln\left(\frac{z}{z_0}\right)}{\ln\left(\frac{z}{z_0}\right)}\right)^2\right]^{1/2} \qquad (6)$$

where the δ indicates the uncertainty in the value that follows the symbol.

Assuming a typical air temperature of 27°C, a relative humidity of 23%, a wind speed of 2.5 m/s, a lake surface temperature of 23°C, a measurement height of 3 m and an uncertainty in z_0 of 25% from our measured value during of the intensive campaign of 0.00055 m, and using the manufacturer's estimates for the uncertainty of the instruments, the following estimate for the fractional uncertainty can be obtained:

$$\frac{\delta LE}{LE} = \left[\left(\frac{0.00042}{0.0205}\right)^2 + \left(\frac{0.2}{300}\right)^2 + \left(\frac{0.2}{3.0}\right)^2 + \left(\frac{0.0334}{8.60}\right)^2\right]^{1/2} = 8.9\% \qquad (7)$$

This estimate of the uncertainty is somewhat deceptive. It assumes a perfect surface and ideal conditions (in other words, it assumes that the theory completely and perfectly describes the phenomena). Elephant Butte Reservoir is a narrow lake in the middle of an arid region and far from ideal. The influence of advection (hot dry air from land) on the local evaporation rate cannot be discounted. This is especially true depending on from what direction the wind is blowing, particularly winds with easterly or westerly components.

IV. RESULTS FROM ELEPHANT BUTTE

In order to estimate how well the proposed method determines evaporative losses over the lake, we will use the data already taken over the lake just as one would if the concept was implemented. There is one free parameter that must be evaluated; the surface roughness parameter, z_0. We will use the data from the intensive campaign that was conducted from 12 to 24 September 2001 to determine this parameter and then apply it to the remainder of the data to determine the effectiveness of the method.

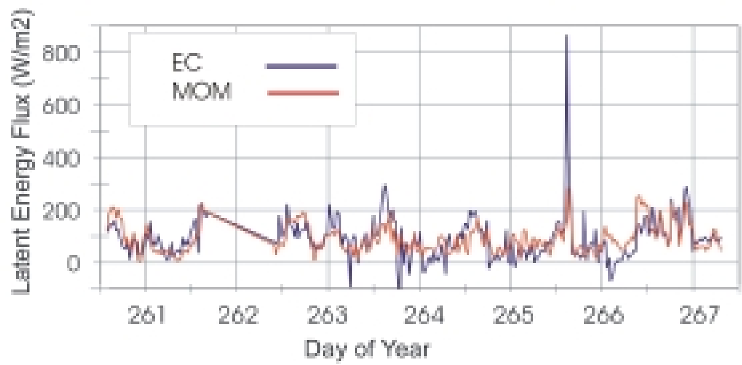

Figure 8. A plot of latent heat flux measured with eddy covariance and computed using the Monin-Obukhov method over the intensive period.

During the intensive period, eddy covariance measurements were recorded at20 Hz. The evaporation rates derived from the eddy covariance method is taken as the truth set from which the roughness parameter is derived. The method described in appendix 1 is used to analyze the data. The roughness parameter is optimized by requiring the minimum rootmean square difference between the Monin-Obukhov derived evaporation rates and the eddy covariance derived evaporation rates to be a minimum. This criterion was developed so that the MOS method is as accurate as possible on a short term basis, not just as a monthly average. The time-series of 30 minute latent energy fluxes from both the eddy covariance instruments and the MOS model is shown in figure. 8. Figure 9 shows the comparison between "filtered" MOS derived evaporation fluxes versus the eddy covariance fluxes during the intensive period.

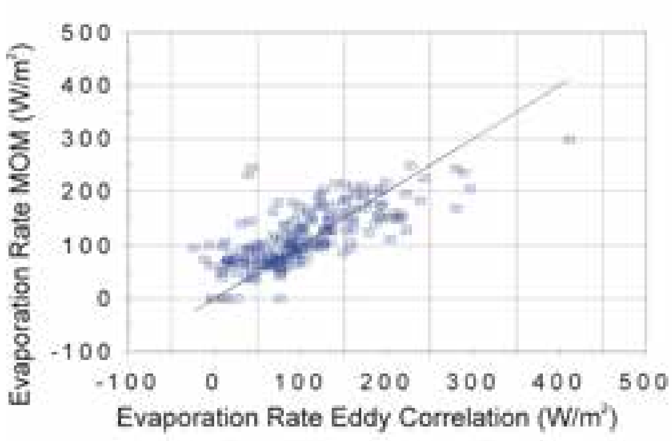

Figure 9. A plot of the eddy covariance rate determined by the Monin-Obukhov method versus that determine by eddy covariance. The RMS difference between the two methods is 41 W/m^2.

When the wind is from the north, it must pass through the tower that holds the sonic anemometer. This creates artificial turbulence that distorts the measured evaporation rate. Because of this, all of the data within 30 degrees of north was filtered and eliminated from the data set. Using an iterative best-fit technique, the optimized value of the roughness parameter is $7x10^{-5}$m. This produces a root mean square difference between the values of the evaporation rates of 41 W/m^2 during the intensive period. Over the duration of the intensive period, the total evaporation, as determined by the eddy covariance method, is 15.86mm and that by the proposed method 17.07mm. The difference between them is approximately 7.6%, a value consistent with the theoretical analysis above.

The value of the roughness parameter determined for the intensive campaign was applied to the data measured at the tower site for the rest of the year, days 266 through 365 of 2001. A comparison of the estimated evaporation rates and the measured evaporation is shown in figure 10. The differences between the measured and estimated values are in some cases much larger than in figure 9. The RMS difference between the measured and estimated values is 58 W/m^2. However, as can be seen in figure 11, the difference between the daily average evaporation rates is much smaller. Over this period, the average measured evaporation rate was 92.6 W/m^2 and the estimate is 94.6 W/m^2. The RMS difference between the daily averages is 8.4

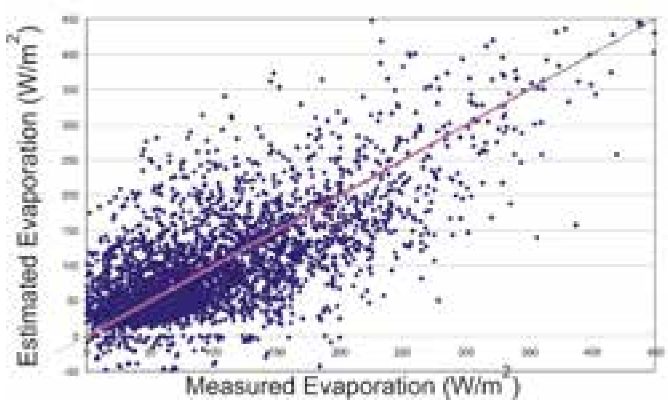

Figure 10. A comparison of the evaporation estimates of the Monin-Obukhov method and those obtained from the eddy covariance instruments for days 266 through 365 of 2001. Data was excluded if the wind was coming from within 30° of north.

W/m², which is consistent with the theoretical prediction. It would be fair to say that while the individual measurements may be significantly in error, the average estimates over periods as short as a day are quite accurate.

The reason for this behavior can be seen in figure 12. This is a comparison of the measured and estimated vertical momentum flux, u*, also known as the "friction" velocity. The black line indicates a one to one comparison. There may be as many two other common relationships that apply. This could be the result of two different processes. The first is the result of differences in wind direction. Winds blowing from the west will have different turbulent characteristics than winds blowing along the lake, from the north or south. Similarly, winds from the east, blowing over the bluffs will have different turbulent characteristics as well. This is especially true as the reservoir contracted (due to drought conditions) during these months; the influence of the nearby land surface should have been increasingly pronounced. The method, as implemented, assumes no directionality.

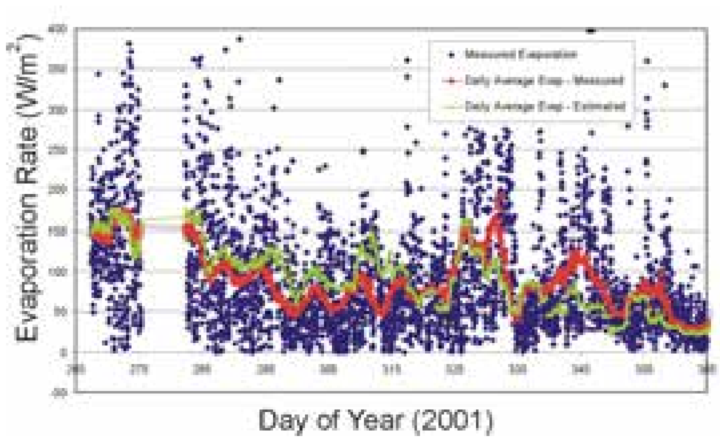

Figure 11. A comparison of the daily average evaporation estimates of the Monin-Obukhov method and those obtained from the eddy covariance instruments for days 266 through 365 of 2001. The green line is the estimate and the red is the measured.

The surface roughness of a water body changes as the wind speed increases (i.e. the waves get larger). Thus the roughness parameter, z_0, should be a function of the wind speed. For most common wind velocities, the adjustments are minimal. However, as the wind speed becomes large, the surface

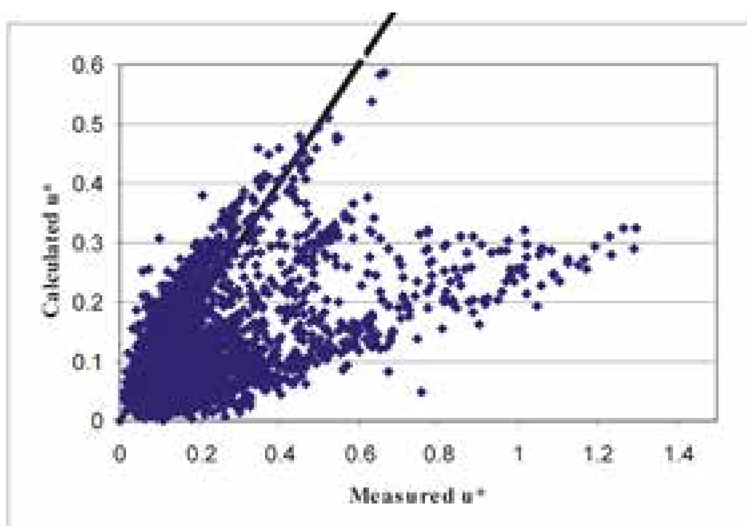

Figure 12. A comparison of the vertical momentum flux, (u*) estimates from the Monin-Obukhov method and those obtained from the eddy covariance instruments for days 266 through 365 of 2001. The black line indicates a one to one correspondence.

roughness also increases, increasing the vertical momentum flux (and the estimated evaporation rate). As can be seen in figure 12, the method seriously underestimates the momentum flux when the momentum flux is large. As an academic exercise, methods could be developed to adjust the values of the surface roughness based on wind speed and direction. However, in a practical sense, attempting to increase the accuracy of the method below 8 % is probably a wasted effort as the comparison "truth" set is not accurate to better than about 10 %. Given the variability of the depth of the reservoir (and thus the area it covers), the influence of the surrounding land surfaces is quite variable.

These phenomena can be seen in figure 13, which shows the traces of all of the relevant data over an eight day period following the intensive campaign. The top graph is a comparison of the measured and estimated fluxes. Those times when the differences between the measured and estimated evaporation rates are greatest occur when the measured fluxes are near zero or at their largest. The periods with high evaporation rates (time increments 170, 220, and 270) are associated with high wind speeds. While the surface and air temperatures and humidities vary in a regular fashion, little occurs that would cause large variations in the estimated evaporation. The periods with near zero measured evaporation rates (time increments 100, 150, 200, and 250) are associated with wind directions near zero or 360° (north). As mentioned previously, these are an instrument artifact due to the presence of the tower. Note that the proposed method estimates evaporation rates during these periods that are more realistic than the eddy covariance method.

On a theoretical basis there is an issue with the treatment of z_0 as applied here. Strictly speaking, the appropriate gradient of specific humidity should be between the height of the roughness length for water vapor and the height, z, where the temperature and humidity measurements are made. The specific humidity at the lower level is an aerodynamic humidity, analogous to the aerodynamic temperature. Since aerodynamic humidity measurements a few millimeters above a waving water surface cannot really be known, the humidity at the water surface is used instead. This approach has been attempted for heat, using the radiometric temperature with inconsistent results. Adjustments have been attempted, adding an excess resistance, or redefining the roughness length to account for choosing the wrong boundary condition. However, research done with sensible heat fluxes have never really resolved this issue. This issue is important when the surface has a significant canopy, where the surface temperature is somewhat ambiguous and

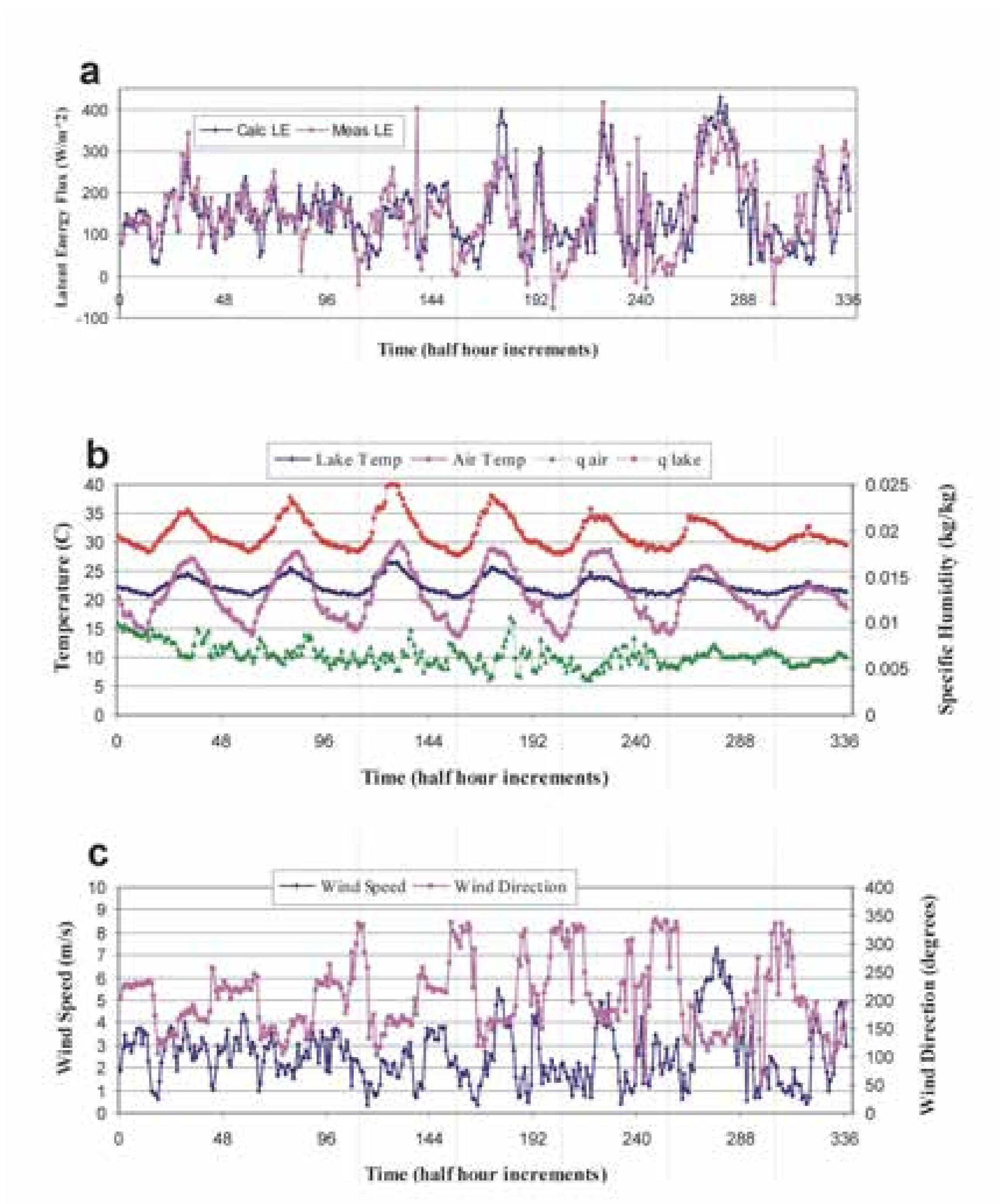

Figure 13. a.) A comparison of the measured and estimated evaporation rates over a 8 day period. b.) The surface and air temperatures and humidities and c.) The wind speed and direction. Note that the periods of large disagreement between the measured and estimated fluxes are periods of high winds.

where the height, z_0, is significant. Over a reservoir such as Elephant Butte, the estimated value of z_0 is a fraction of a millimeter, so the difference between the specific humidity at the surface and at the height, z_0, is minimal.

In order for water management efforts to be effective, decision making must be accomplished on time scales of approximately a week (or the time it takes for water to travel the distances between the major reservoirs). Thus estimation methods must be accurate on time scales shorter than that to be effective or useful. Further, the methods used should be predictive. The fact that the proposed method can be used with weather prediction data to project the evaporation estimates into the future to be a major advantage.

V. COMPARISON TO PAN MEASUREMENTS

Pan evaporation is one of the oldest and simplest methods of measuring open water evaporation with continuous measurements in some places dating back nearly 120 years. The measurement involves placing a pan in open area and measuring how much water evaporates during a period of time. The amount of evaporation as measured from the pan is used to estimate the actual evaporation over an area through the use of a coefficient known as the "pan coefficient, (K_p)". Evaporation pans are commonly used to estimate lake evaporation as $E_{lake} = K_p E_{pan}$, where E_{lake} is the lake evaporation and E_{pan} is the pan evaporation. A limitation of this methodology is that the pan coefficient is considered to be dependent on the local environment around the pan, the type and size of pan used, and on the manner in which the pan is operated and managed. It is well-known that pan evaporation differs from lake evaporation for a number of reasons. These factors have been outlined by Dingman (2002) and include the difference in the heat-storage capacity of the pan, the lack of surface-or ground-water sources, and, with raised pans, energy transfer from the sides exposed to the air and sun. The pan coefficient used by the Bureau of Reclamation is 0.7.

Data from two Class A pans are available. One was located on a bluff at the south end of the reservoir. The other was located at Monticello point, just to the south-west of the tower site. The manufacturer of the pans (BCP electronics) estimates the resolution for the automated pan at 0.1mm (0.004in). Because of the way the instrument functions, when the amount of rainfall was greater than 10mm, the total pan evaporation was recorded as 0 mm (no evaporation) while days in which the rainfall was less than 10mm pan the evaporation

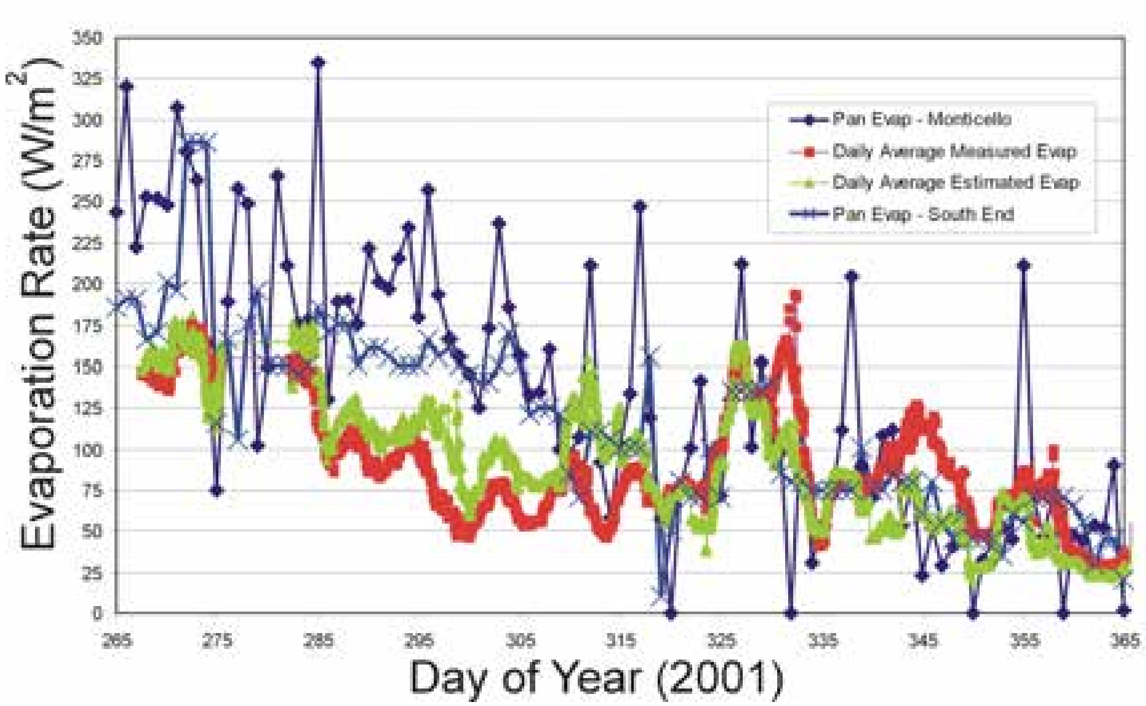

Figure 14. A plot of the measured evaporation rate, the proposed estimation method and the two pan estimates. Because of solar heating of the pan, the pan estimates for the summer months is nearly twice the actual rate.

was recorded as less than 0.5mm/day.

A comparison of the pan evaporation estimates is shown in figure 14. The agreement appears to be quite good in the last part of the measured period. However, the pans greatly overestimate the evaporation in the summer months. This is because the pans have a small albedo and are not connected to the ground. They absorb a great deal of solar energy during the day, making the water in the pan quite warm. The higher water temperature increases the vapor deficit over the pan and thus the amount of water that evaporates from the pan. The consistent overestimation of the evaporation can be seen in figure 15. Over this period, the average measured evaporation rate was 92.6 W/m^2 , that from the proposed method was 94.6 W/m^2 (difference), that from the south pan is 140.9 W/m^2 and that from the pan on Monticello point was 116.8 W/m^2. The RMS difference between the daily average of the proposed method and the measured evaporation is 8.4 W/m^2, while the RMS differences between the pan estimates and the measured evaporation is 68.7 W/m^2 (South end) and 45.8 W/m^2 (Monticello Point). The long term pan measurements greatly overestimate the amount of evaporation, especially during the summer. On a daily basis, the average error is on the order of 50% to 75%.

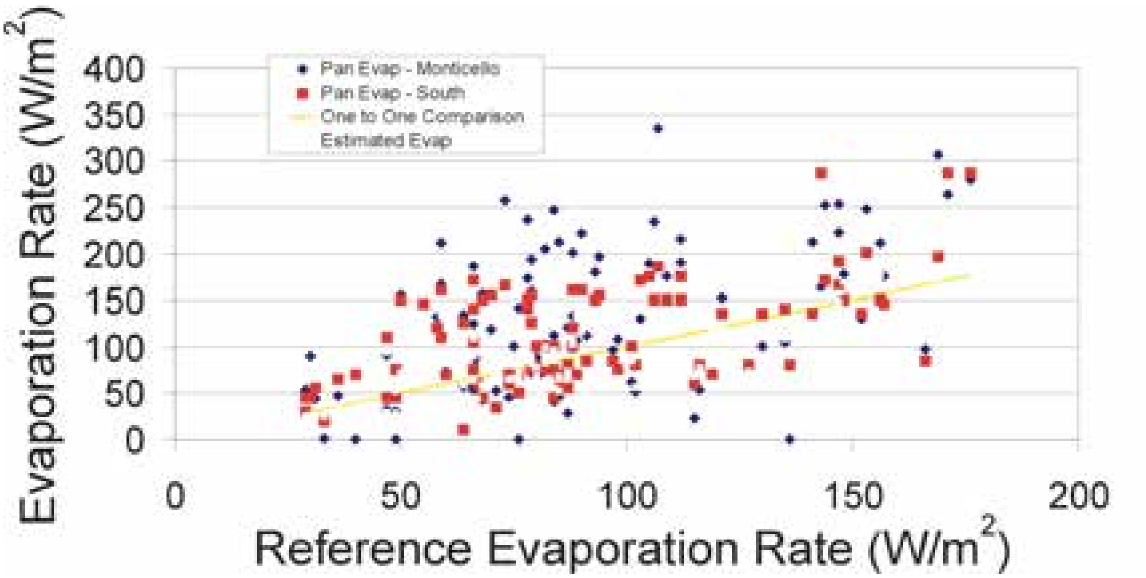

Figure 15. A plot of the pan evaporation estimates vs the measured evaporation rate. Note that the pan consistently overestimates the actual evaporation rates.

VI. CONCLUSIONS

This report proposes a method to estimate the evaporation rates over open water surfaces using basic data easily acquired from slightly modified meteorological stations. A series of measurements made at Elephant Butte in 2001 were used to show the method and determine the accuracy that could be expected. The data from a week long intensive campaign were used to compute the surface roughness parameter, the only variable that requires determination. The method was then applied to the data for the remainder of the year using the computed surface roughness.

The uncertainty associated with the method is estimated to be approximately 9 percent. Some measures of the uncertainty (long term averages) are substantially less, but the half-hourly values have an RMS difference that can be much larger. The daily estimated values are highly consistent with the measured values with an RMS difference of about 9 percent. The ability of the method to deliver accurate estimates over short time periods as well as its ability to use meteorological forecasts make it possible to use the method in a predictive mode.

While the measurements did not last the entire year, the evaporation rate did not change radically throughout the year (see figure 7 for example). Because of this we can estimate the total amount of water lost to evaporation from the reservoir during a year's time.

Over the course of a five day intensive measurement period there was a reliable estimate of a loss of 4.14 mm a day. For a conservative estimate, we reduce the loss to a yearly average of 3 mm/day (the reservoir is at its warmest in September, at the end of the summer). This compares to the measured average of 92.8 W/m^2, or 3.3 mm/day over the last 100 days of 2001. An evaporation rate of 3 mm/day is approximately 1.1 meters of water lost (3.6 feet) over the course of a year. In recent years, Elephant Butte Reservoir has been significantly below its full capacity of 36,500 acres and is currently at its lowest levels in years. Assuming that the reservoir is half full, or more specifically that the reservoir occupies half of its maximum surface area (Elephant Butte Reservoir is unusual in that in addition to a deep channel, a large part of the reservoir, when full, is relatively shallow). Assuming the reservoir occupies half of its potential surface area, the annual losses that can be expected to be about 66,000 acre-feet. By way of comparison, the annual releases from the reservoir are on the order of 800,000 acre-feet. Depending on the annual climate and the size of the reservoir, the amount of water lost through evaporation for just the Elephant Butte reservoir can be expected to range between 8 and 20% of the amount of water released from the reservoir for use downstream.

The technique developed here for open water evaporation estimation requires only basic data that can be acquired from simple meteorological stations. The evaporation model described in this report uses a well-known turbulence averaging parameterization that is widely accepted and used. Unlike previous approaches which were highly empirical and dependent upon highly variable "calibration coefficients", the technique proposed here is a soundly rooted, science-based method. It is expected that this method can be applicable to all open water bodies.

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APPENDIX 1. MONIN OBUKHOV METHOD

The Monin-Obukhov Similarity method (MOS) is a turbulence averaging scheme that uses basic meteorological observations to estimate the turbulent heat and momentum fluxes, including sensible (H), latent (LE), and momentum (u_*) fluxes. Equations 2a-c described above are simultaneous equations for the gradients of temperature, specific humidity, and wind speed that must be solved iteratively since the stability functions (and more specifically, the Monin-Obukhov length, L) are dependent upon the values of the energy and momentum fluxes that are being estimated.

If the gradient of temperature between the surface and air is positive, the atmosphere is stable and L will be positive. If the gradient is negative, the atmosphere is unstable and L is negative. A complete description of the nature and behavior of stability functions in the lower atmosphere can be found in Stull, 1988. The other important variable is the roughness length, z_0 which must be specified, and is on the order of a few millimeters at most over water (Brutsaert, 1982).

The proposed method uses basic meteorological observations of the average air temperature, T, water surface temperature, Ts, water vapor concentration, q, and wind speed, u, at some height above the water surface, z, over a time period ranging from 15 to 30 minute. Lower boundary conditions are set by assuming that:

A. the wind speed at the surface (subscript s) is zero, and

B. the water vapor concentration at the surface is at saturation for the current temperature of the water surface temperature. The saturation vapor pressure can be found using the Clausius-Claperon or similar equations (Brutsaert, 1982).

Lastly, the atmosphere is assumed to have a neutral stability for the first iteration of the calculation, i.e., L is set to 1000. The fluxes of energy and momentum are calculated assuming a neutral atmosphere. L is then computed from the initial flux estimates (Eq. 3), which in turn allows the stability functions to be estimated as well. These stability functions are used to calculate an improved estimate for the fluxes. This process is iterated until the values for the fluxes converge. The iteration process usually requires 3 to 4 cycles. Figure 16 is a flowchart for the iterative calculations.

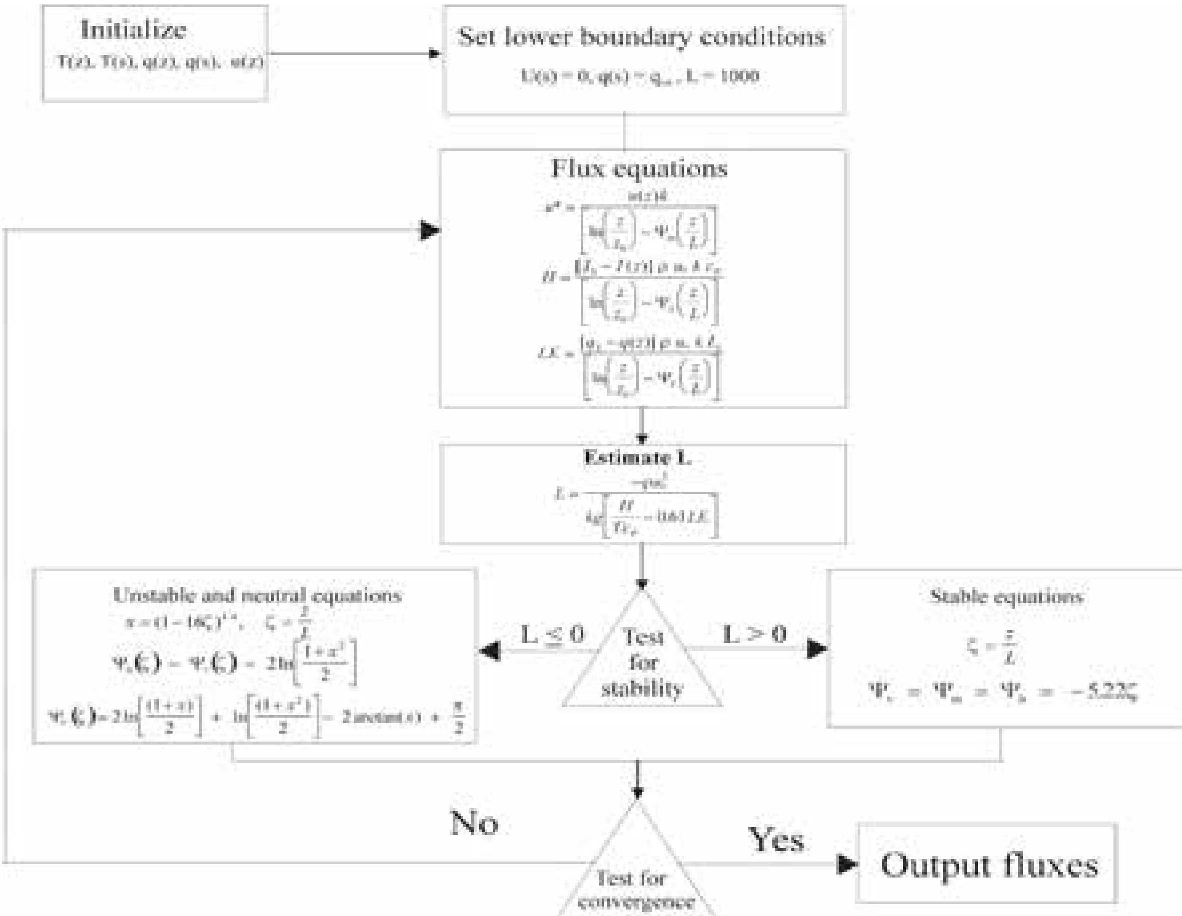

Figure 16. Flow chart of Monin-Obukhov method using meteorological data.

APPENDIX 2. AVAILABLE DATA SETS

EBWaterThermocoupleTemperature

Quattro file containing water temperature at depth for days 235 through 332 of 2001. This is the corrected temperature.

EB_2001HourlyMetData

Excel file containing IRT surface temperature and computed net radiation for days 255 through 270 of the intensive campaign.

ElephantButteComputedRadiationData

Excel file containing details of the computations for net radiation for days 255 through 270 of the intensive campaign.

ElephantButteIntensiveData

Excel file containing the tower data for days 260 through 267 of the intensive campaign.

ElephantButteIntensiveMetData

Excel file containing the tower data along with eddy covariance calculations for days 260 through 267 of the intensive campaign.

nlake weather station2003

Excel file containing the weather station data for the first two months of 2003.

nlake3dRAW_2001Working

Excel file containing all of the tower data along with eddy covariance calculations for 2001.

radiation4a

Excel file containing details of the computations for net radiation for 2001.

slake weather station2003

Excel file containing the weather station data for the first two months of 2003.

Elephant Butte Elevation Surface Area Table

A table containing the surface area of Elephant Butte Reservoir as a function of the water level.

PanEvaporationfor2001

Quattro file containing the pan evaporation data from the station at the south end of the reservoir.