ESTIMATING EVAPORATION FROM ELEPHANT BUTTE RESERVOIR WITH THE MONIN-OBUKHOV SIMULARITY THEORY USING SIMPLE INSTRUMENTATION

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Abstract

The Elephant Butte Reservoir (EBR) plays a major role in the management and distribution of water to southern New Mexico, Texas and Mexico. Official evaporation from EBR is currently estimated from a single Class-A evaporation pan placed on a hill southeast of the reservoir which does not represent the same meteorological conditions as EBR. This study used Monin-Obukhov similarity (MOS) theory to estimate evaporation from EBR using simple instrumentation with an objective to improve evaporation estimates for better management. The estimated evaporation was compared to measured values using the eddy covariance and bulk -aerodynamic methods.

The estimated friction velocity using the MOS ranged from 0.004 to 0.778 m/s with an average of 0.114 m/s and the estimated aerodynamic roughness (z_0) ranged from 1.90 x 10^{-8} m to 8.95 x 10^{-8} m with an average of 3.61 x 10^{-5} m. The MOS estimates were sensitive to changes in z_0. The estimated friction velocity (u_*) was underestimated when compared to measured values using the eddy covariance method. The MOS method estimated higher evaporation rates when compared to the other two methods. Times series of evaporation rates using the three methods showed a similar trend on a 30-minute and daily basis. The study results indicate the MOS is a promising method that could be used to reasonably estimate EBR evaporation rates.

Key words: Elephant Butte Reservoir, Evaporation, Monin-Obukhov Similarity Theory

Introduction

The Elephant Butte Reservoir (EBR) on the Rio Grande plays a major role in the management and distribution of water to southern New Mexico, Texas and Mexico according to the needs of the Lower Rio Grande Project and the terms of the Rio Grande Compact and Treaty of 1906. Due to EBR's large surface area and arid climate, its evaporation is one of the major loss terms in the hydrologic balance of the Rio Grande. Official evaporation from Elephant Butte Reservoir is currently estimated from a single Class-A evaporation pan placed on a hill at the southern end of the reservoir where the meteorological conditions are significantly different. A single pan coefficient is used to compute lake evaporation from pan evaporation measurements. Stage-surface-area tables developed from periodic hydrographic surveys are used to relate the depth measurement of evaporation to the volume of water lost from the reservoir. Pan coefficients are highly variable and depend on climate, season, and local conditions. It is of practical importance that simple methods of estimating reservoir evaporation be developed to improve the management of this important resource.

The main goal of this work is to develop a better method of determining evaporation from EBR. The proposed work was an application of the Monin-Obukhov Similarity Theory to estimate the reservoir evaporation. Unlike the current methodologies used such as the three-dimensional eddy covariance technique, this methodology does not require specialized expertise in its deployment nor expensive instrumentation.

The Elephant Butte Reservoir on the Rio Grande is located (N33°09'15"; W107°11'30" WGS84 Datum) in south central New Mexico about 4 miles from the city of Truth or Consequences as shown in Figure 1. The Reservoir was constructed from 1911 to 1916 with an estimated capacity of 2,638,860 acre-ft in order to control downstream flooding, to provide water for irrigation from the Rio Grande and to provide hydroelectric power. At full capacity, the Reservoir extends approximately 40 miles long and varies in width from 2 to 4 miles. It was reported by Gunaji (1968) as having a capacity of 2,194,990 acre-ft and covering a surface area of approximately 36,580 acres at the spillway elevation of 4407 ft. The current capacity is estimated at 2,065,010 acre-ft. The decrease in capacity is attributed to accumulation of sediment.

Methodology

Moninin-Obukhov Similarity (MOS) Theory using an iterative technique was used to estimate EBR evaporation rates. For verification of the MOS technique, the results were compared to measured evaporation using both the eddy- covariance and bulk-aerodynamic methods. Results were compared for a period of measurement from June through December of 2007.

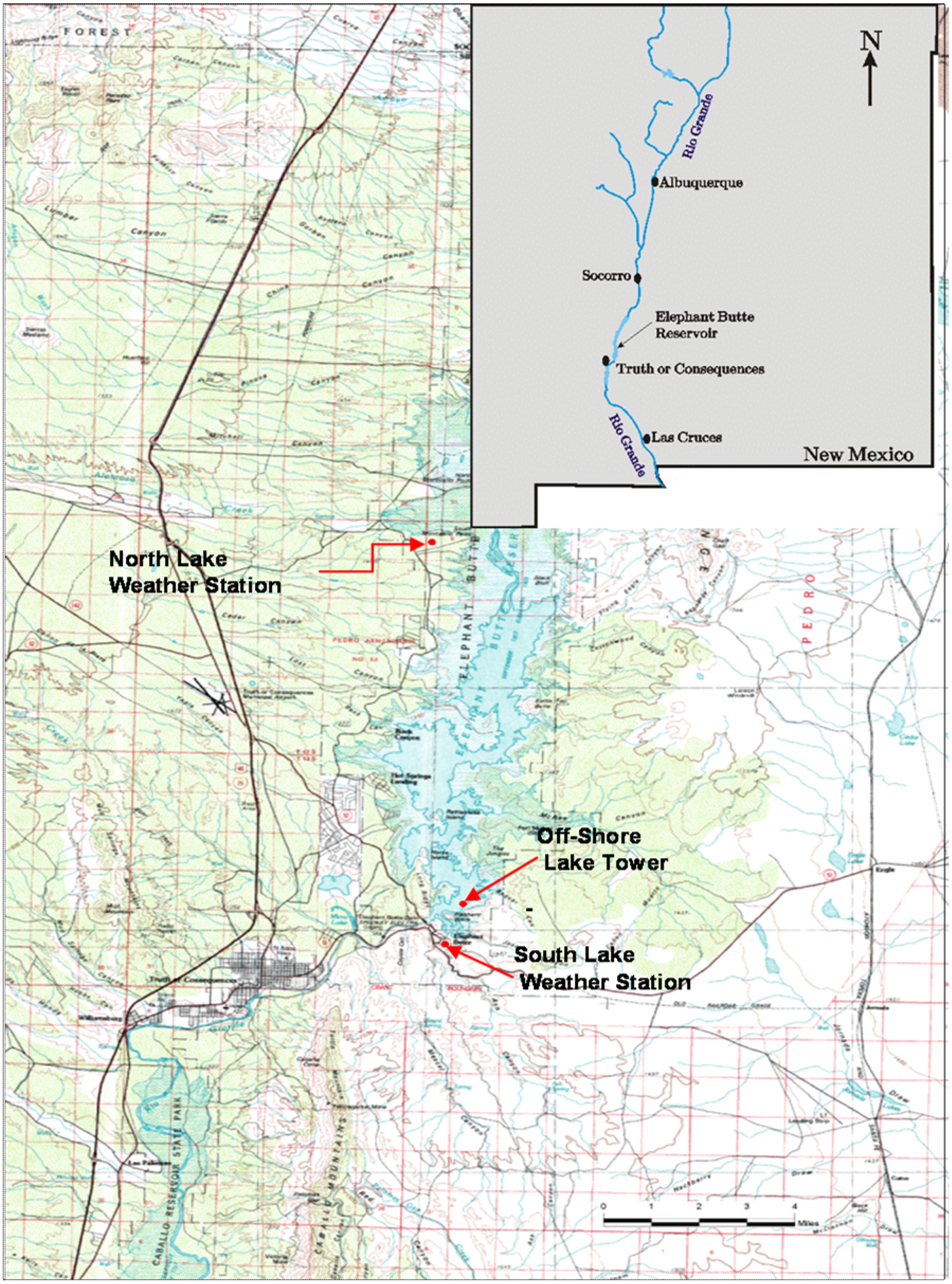


Figure 1. Location of Elephant Butte Reservoir and research stations

Monin-Obukhov Method

Over ideal homogeneous surfaces, the 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, water vapor concentration, and the wind speed at any height within the surface layer can be expressed using Equations 1-3. The stability functions in Equations 1-3 are scaling functions which depend on the measurement height, surface roughness, and the turbulent structure of the surface layer. The MOS method cannot be used under calm winds or when the friction velocity approaches zero (Stull 1988).

The method requires only simple instrumentation including wind speed, temperature, and humidity at some height above the surface as well as the temperature at the water surface (See Figure A and B in the Appendix). At the surface, the wind speed is assumed to be zero since the shear stress of the wind is transferred to the water in the form of waves and the air immediately above the lake surface is assumed to be saturated. The energy fluxes and friction velocity are dependent on each other and thus must be iteratively solved. The aerodynamic roughness is typically a constant over land surfaces. However the interaction between turbulent air and a free water surface involves complicated physical phenomena and therefore the prediction of the aerodynamic roughness over water is still subject to some uncertainty (Brutsaert 1982). An empirical formula by Charnock (Equation 4) as reported by Brutsaert (1982) was used to estimate the roughness as a function of friction velocity. Since the roughness is a function of friction velocity it too must be solved iteratively. Equations 1 through 4 are as follows:

$$\overline{T}_s - \overline{T}_z = \frac{H}{k u_* \rho c_p}\left[\ln\left(\frac{z}{z_0}\right) - \psi_{sh}(\zeta)\right] \tag{1}$$

$$\overline{q}_s - \overline{q}_z = \frac{E}{k u_* \rho}\left[\ln\left(\frac{z}{z_0}\right) - \psi_{sv}(\zeta)\right] \tag{2}$$

$$\overline{u}_z = \frac{u_*}{k}\left[\ln\left(\frac{z}{z_0}\right) - \psi_{sm}(\zeta)\right] \tag{3}$$

where,

$\overline{T}_s =$ Temperature of the surface

$\overline{T}_z =$ Temperature at height z

$H =$ sensible heat flux

$k =$ von Karman's constant

$u_* =$ friction velocity

$\rho =$ densisty of air

$c_p =$ specific heat capacity

$z_0 =$ aerodynamic roughness length

$z =$ height

$\overline{q}_s =$ specific humidity at the surface

$\overline{q}_z =$ specific humidity at height z

$E =$ evaporation flux

$\overline{u}_z =$ wind speed at height z

$g =$ gravity

$\psi_{sh}(\zeta),\ \psi_{sv}(\zeta),\ \psi_{sm}(\zeta) =$ stability functions

and,

$$\psi_{sh}(\zeta) = \psi_{sv}(\zeta) = 2\ln\left(\frac{1+x^2}{2}\right)$$

$$\psi_{sm}(\zeta) = 2\ln\left[\frac{(1+x)}{2}\right] + \ln\left[\frac{(1+x^2)}{2}\right] - 2\arctan(x) + \frac{\pi}{2}$$

$$x = (1-16\zeta)^{1/4}; \qquad \zeta = \frac{z}{L}$$

$$L = \frac{-u_*^3\rho}{kg\left(\frac{H}{T_z c_p} + 0.61E\right)}$$

$$z_0 = \frac{u_*^2}{bg} \tag{4}$$

$b =$ constant $\approx$ 0.015

Eddy Covariance Method

The eddy-correlation method, also known as eddy-covariance, can be considered as a direct method for evaporation when applied directly over the surface where sufficient fetch distance is present. The eddy-covariance method can be used to estimate momentum, latent and sensible heat fluxes over the surface of a water body, of which the latter two are important for energy budget techniques. It is the most reliable and direct measurement of turbulent exchanges in the atmosphere (Arya, 2001). Therefore, eddy covariance is a good method to conduct evaporation studies on a reservoir. In the past, measurements of evaporation by eddy-covariance were limited by the relatively slow response of air moisture sensors. However, currently available hygrometer sensors can now be used in conjunction with a sonic anemometer at sampling rates of up to 60 Hz. This significantly faster sampling rate allows measurements to be taken considerably closer to the water surface thus reducing the fetch distance required for accurate measurements.

The eddy-covariance method is based on correlating fluctuations of vertical wind speed and scalar properties, such as water vapor or temperature in the lower atmospheric boundary layer to obtain latent and sensible flux densities, respectively. The sensible heat and latent heat flux densities within the surface layer can be written as:

$$H = \rho \cdot c_p \cdot \overline{wT} \tag{5}$$

$$LE = \lambda \cdot \overline{w\rho_v} \tag{6}$$

Where,

H	=	sensible heat flux
LE	=	latent heat flux
λ	=	latent heat of vaporization of water
$\overline{w\rho_v}$	=	covariance of vertical wind speed and vapor density
$\overline{wT}$	=	covariance of vertical wind speed & air temperature

The eddy covariance system included a sensitive three-dimensional sonic anemometer (CSAT3) and a fast response krypton hygrometer (KH2O) (See Appendices 1C and 1D). Campbell Scientific CR23X and CR5000 data loggers were used to average and record the data collected at 10 hertz. Ideally a sonic anemometer is coupled with a fast response fine (10-25 μm diameter) wire thermocouple to estimate sensible heat fluxes. The fine wire thermocouples are very delicate and raindrops or even fine sand from a wind gust can easily destroy the thermocouple. As an alternative, sonic anemometers can estimate sensible heat fluxes without a thin wire thermocouple using sonic virtual temperature. This is explained in detail by (Schotanus et al., 1983). Sensible heat fluxes were corrected for sonic temperature using the Schotanus method. In addition, the three-dimensional wind speed and eddy covariance data collected were corrected for rotation according to Tanner and Thurtell (1969) and also as described by Lee et al. (2004). Sensible and latent heat fluxes were corrected for water vapor density effects according Webb et al. (1980).

The latent heat flux measured by krypton hygrometer was corrected for oxygen density concentration according to Van Dijk et al. (2003) and as recommended in the Campbell Scientific Inc. *Instruction Manual* (1998). In the field setup, the KH2O is displaced spatially (10-20 cm) from the sonic anemometer. This spatial displacement reduces the correlation between the measurements of vertical velocity and scalar concentration. A formula for the associated flux loss was derived by Horst (1997) to correct for this displacement.

Bulk-aerodynamic Method

The bulk-aerodynamic method, which is based on the Dalton-type equation and Fick's first law of diffusion, can be used to estimate sensible heat and latent heat fluxes through a fixed boundary layer such as that developed over the free water surface of a reservoir (Dingman, 2002). It is based on the concept of mass transfer theory, which states that the diffusion of heat and water vapor into the atmosphere moves from where its concentration is larger to where its concentration is smaller at a rate that is proportional to the spatial gradient of that concentration. This method is straightforward because it relies on relatively routine measurements of wind speed, air temperature, relative humidity, and water surface temperature. Assuming that the boundary layer over a smooth water surface is similar to that over a rough water surface, the following equations could be used to determine sensible and latent heat fluxes (Hicks, 1975):

$$H = C_H \cdot c_p \cdot \rho_a \cdot u_{10} \cdot (T_s - T_a) \tag{7}$$

$$LE = C_E \cdot \lambda \cdot \rho_a \cdot u_{10} \cdot (q_s - q_z) \tag{8}$$

Where,

C_H = bulk transfer coefficient for sensible heat
C_E = bulk transfer coefficient for latent heat
u_{10} = wind speed at 10 m reference height above surface
T_s = water surface temperature
T_a = air temperature [°C]
q_s = saturated specific humidity at water-surface temperature
q_a = specific humidity

Under near neutral conditions the following relationship can be assumed (Hicks, 1975).

$$C_E \approx C_H \tag{9}$$

For wind speeds between 4 to 20 m/s, it was proposed by Kondo (1975) that C_H and C_E ranged from $1.15 \text{x} 10^{-3}$ to $1.26 \text{x} 10^{-3}$ and $1.18 \text{x} 10^{-3}$ to $1.30 \text{x} 10^{-3}$, respectively. Thus a mean value of 1.22 $\text{x}10^{-3}$ would be reasonable for application over water. Based on Brutsaert (2005), numerous experimental determined coefficients above the ocean on average show $C_E \cong C_H \cong 1.2(\pm 0.30) \times 10^{-3}$ for certain range of normal wind speeds (neutral conditions satisfied) at 10 m above the surface. The specific heat capacity of moist air was calculated using the empirical equation presented by Jensen et al. (1990), referencing Brutsaert (1982) as a function of specific humidity:

$$c_p = c_{pd} \cdot (1 + 0.84 \cdot q) \tag{10}$$

Where,

c_p = heat capacity of air at constant pressure
c_{pd} = specific heat of dry air
q = specific humidity

The bulk-aerodynamic method has been used successfully to estimate evaporation from Lakes Mead and Hefner (Harbeck, 1962) using fairly simple instrumentation. Despite successful estimates at Lakes Mead and Hefner, accurate estimates of evaporation were limited due to the technology available at the time to measure surface temperature of water. Current technology of using an infrared thermocouple sensor to measure skin temperature of the reservoir minimizes these shortcomings.

Instrumentation

Originally a 94 ft. tower flux tower was installed at Elephant Butte Reservoir (N33°09'50.76", W107°10'34.44) in 2004. The off-shore lake tower (OSLT) was located in approximately 45 ft of water. The tower base was constructed of reinforced concrete and guyed to pre-cast concrete anchors. The tower was ensured to be vertical and secure so that the sensors could be mounted according to the recommendations of their manufacturers. A floating tower was avoided due to the sensitivity of some of the sensors to motion and deviation from horizontal level. The tower was extended in 2005 to a height of 115 ft, but settlement and sediment accumulation reduced the height to about 108 ft. Figure 2 shows the flux tower (OSLT) with the sensor setup at Elephant Butte Reservoir. Table 1 gives details of the sensors located at the OSLT including their accuracies.

Table 1. Sensors located at the OSLT in Elephant Butte Reservoir

Measurement	Sensor Type (Model)*	Manufacturer	Accuracy
Three-Dimensional Wind Speed (u_x,u_y,u_z)	3D Sonic Anemometer (CSAT 3)	CSI	u_x,u_y ~ 0.02 m/s u_z ~ 0.04 m/s
Latent Heat (LE)	Krypton Hygrometer (KH20)	CSI	Standard Error ~ 0.145 g/m³
Water Surface Temperature (T_s)	Infrared Thermocouple (IRTS-P)	Apogee	± 0.2 °C
Air Temperature (T_a)	Platinum Resistance Temperature Detector (HMP45C)	CSI (Vaisala)	± 0.3 °C
Humidity (RH)	Capacitive Relative Humidity Sensor (HMP45C)	CSI (Vaisala)	± 2%
Horizontal Wind Speed & Direction	05106 Propeller Anemometer	R.M. Young	± 0.3 m/s ± 3°
Barometric Pressure	CS105 Barometer	CSI (Vaisala)	± 0.05 kPa

* All sensors sold through (Campbell Scientific Inc. (CSI), 815 W. 1800 N., Logan, Utah 84321-1784)

Sensor heights were adjusted as the water level in the reservoir increased or decreased at the location. Efforts were made to keep the sensors that are sensitive to height above the surface, especially the CSAT3, KH2O, and the infra-red sensor, within the range of 2 to 4 m above the water surface. The surface temperature, relative humidity, ambient temperature, wind speed, and wind direction data were collected at 1Hz and averaged over 30 minutes. The eddy covariance data were collected at 10Hz and also averaged over 30 minute periods. All the data were either downloaded manually at the site or transmitted to New Mexico State University using a cellular phone telemetry system.

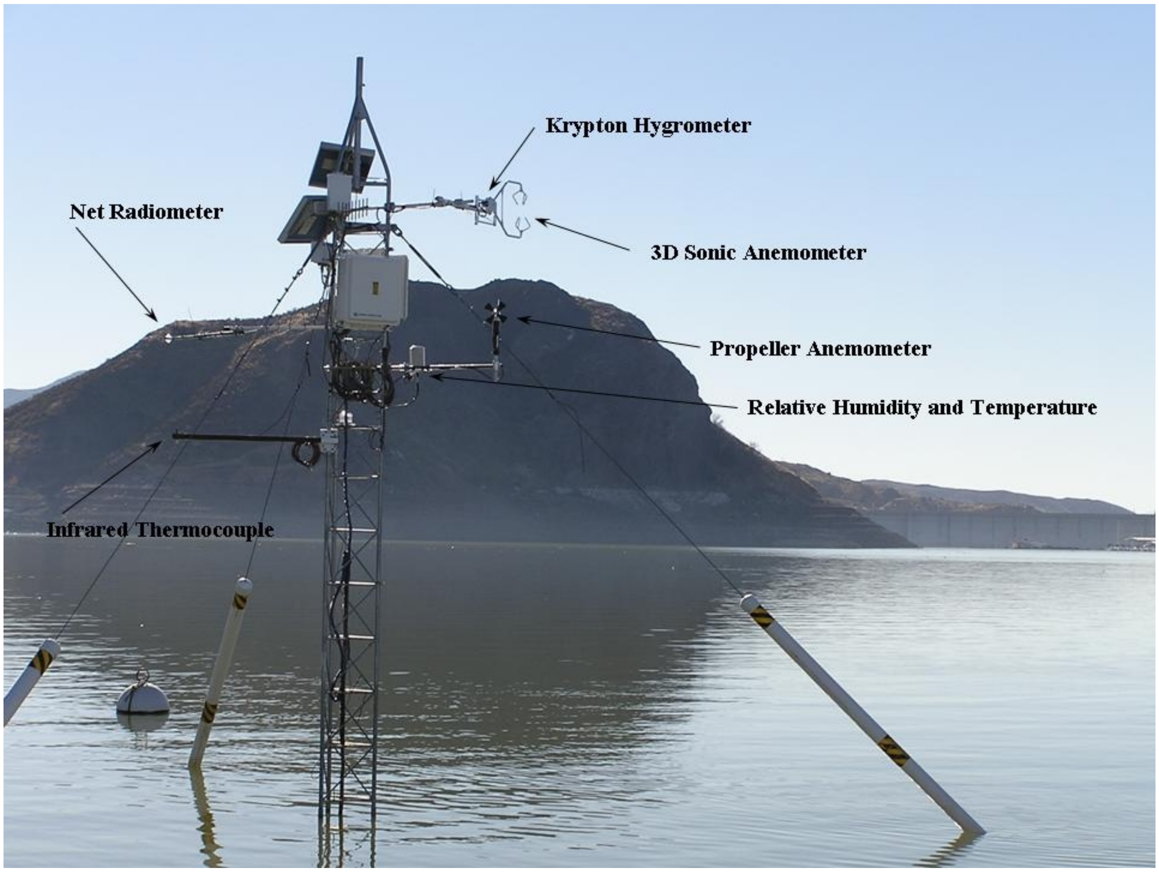


Figure 2. Flux tower with sensor setup at the OSLT in Elephant Butte Reservoir, New Mexico

Results and Conclusions

The energy fluxes, friction velocity and aerodynamic roughness were all found by MOS using an iterative process on the data using Equations 1-4. Thirty minute averages were used as inputs in the process to calculate the fluxes and other parameters. In order to compare MOS estimates with measured eddy-covariance values, the data was filtered to only include valid wind speed not affected by the flow distortions of the tower. In addition, unrealistic data due to calm wind speeds and friction velocities near zero were also filtered due to limitations of the MOS theory.

Six months of valid data were used to compare the methodologies. The estimated friction velocities were compared with measured friction velocities from the CSAT3 sonic anemometer using 30-minute averages. The estimated friction velocity ranged from 0.004 to 0.778 m/s with an average of 0.114 m/s. Figure 3 shows the comparison along with the linear regression equation and the 1:1 relationship line. A large portion of the data follows a 1:1 relationship however in general the estimated friction velocity underestimated the measured friction velocity [estimate u_* = 0.69(measured u_*)-0.01, $R^2 = 0.6372$]. In general at higher wind speeds the estimated friction velocities were lower than the measured friction velocities. The estimated aerodynamic roughness (z_0) using Equation 4 with MOS ranged from $1.895x10^{-8}$ to $8.95x10^{-4}$ m with an average of $3.61x10^{-5}$ m and is consistent with measurements over open water compiled by Stull (1988). The z_0 was observed to greatly influence the MOS flux results.

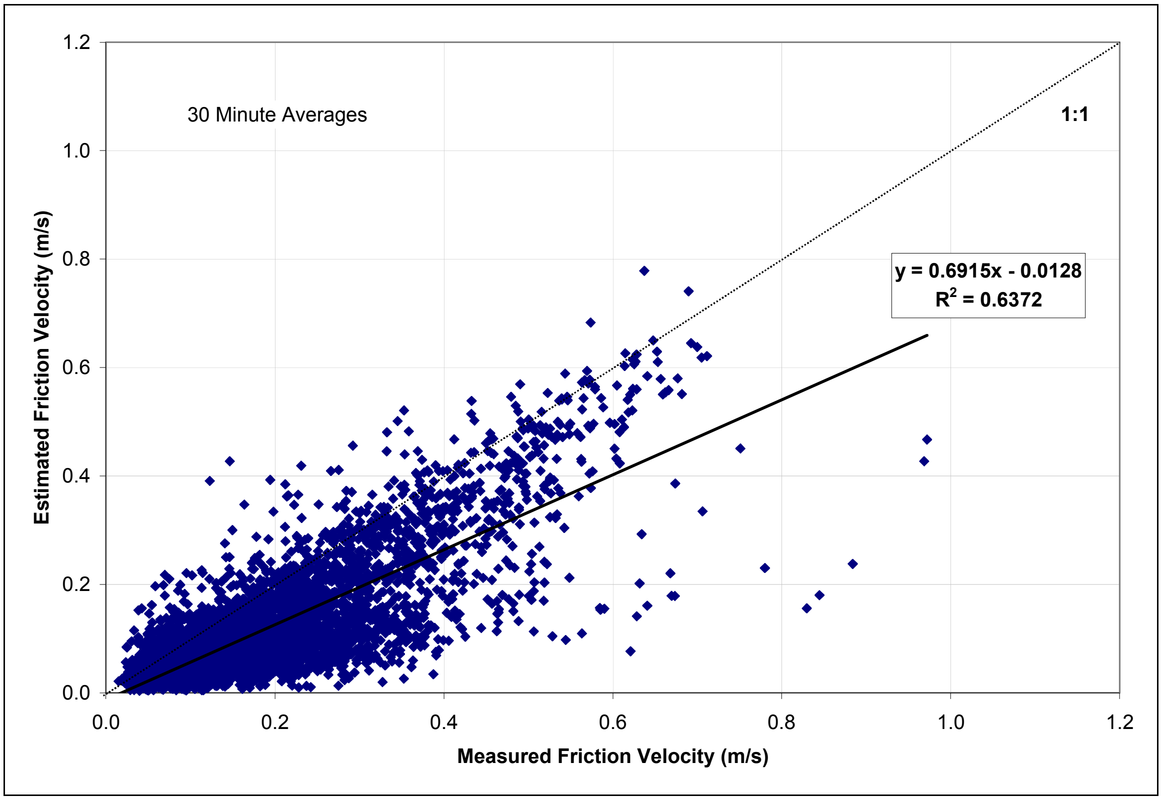


Figure 3. Measured and estimated friction velocity comparison at Elephant Butte Reservoir

Evaporation rates were compared using the three different methods at EBR. Comparison of thirty-minute averages of evaporation rates are shown in Figure 4 as an example. The three methods follow the same trend over the 20 days shown. In general, the MOS estimated higher evaporation rates when compared to the other two methods. The eddy covariance evaporation measurements using the krypton hygrometer (KH2O) were the lowest of the three methods. This was expected due to sensor limitations inherent to the KH2O with long-term field measurements. The MOS and bulk-aerodynamic methods compared reasonably well. Both methods utilized the same input data. However, the two methods are different such that the MOS considers the variability in atmospheric stability while the bulk-aerodynamic assumes near neutral atmospheric conditions.

Daily evaporation rates using the three methods from June to November of 2007 are presented in Figure 5. Evaporation rates ranged from ?? to ?? using the MOS, ?? to ?? using the eddy-covarance method, and ?? to ?? using the bulk-aerodynamic method. The evaporation rates follow the same trend with MOS estimates being higher than the rest of the methods. The results indicate that the MOS is a promising method that could be used to reasonably estimate evaporation of the reservoir using simple instrumentation. Further investigation of the MOS methodology is warranted. For example, the aerodynamic roughness values of the EBR needs to be measured and compared to the empirical equations commonly used.

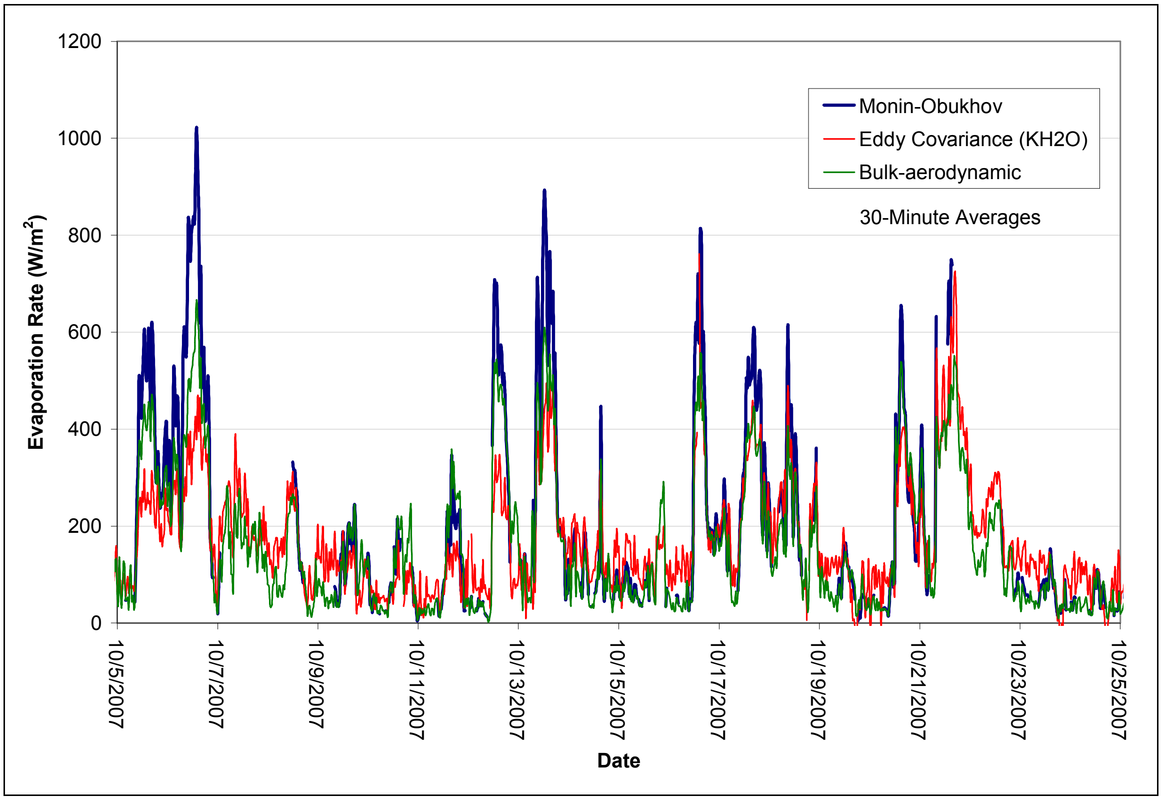


Figure 4. Evaporation rate comparison at Elephant Butte Reservoir using 30-minute averages

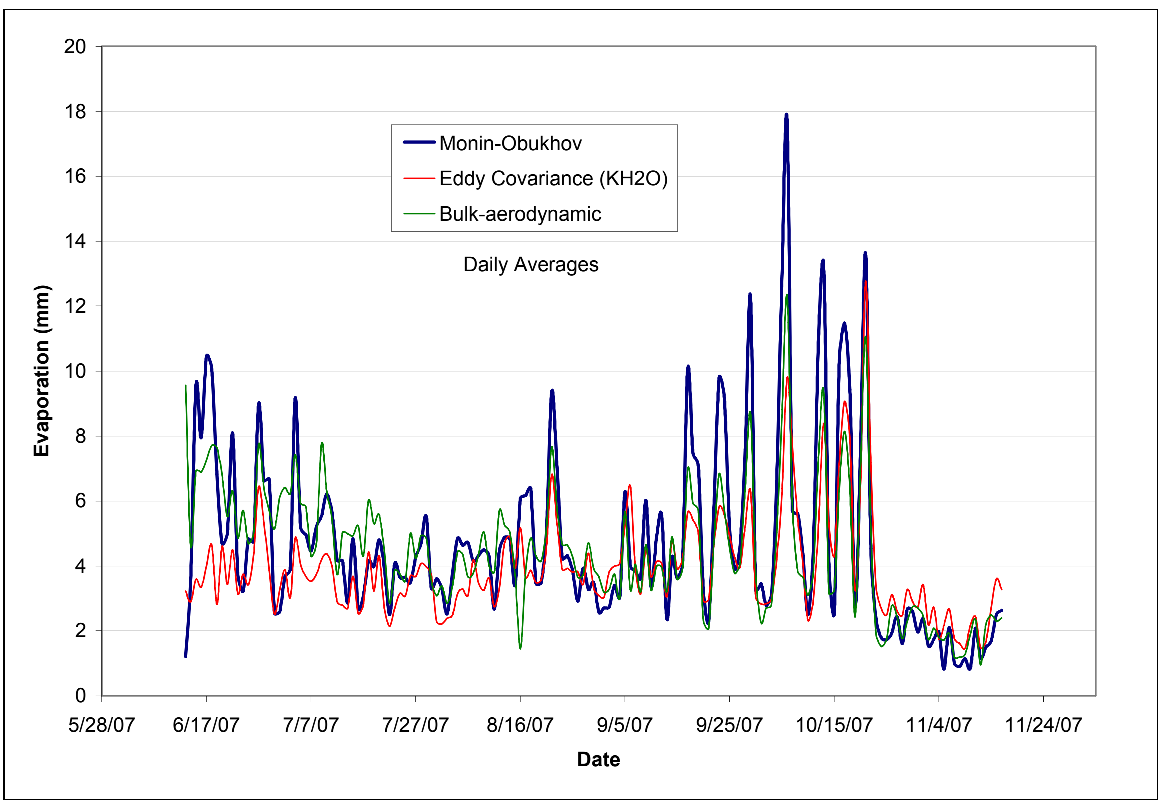
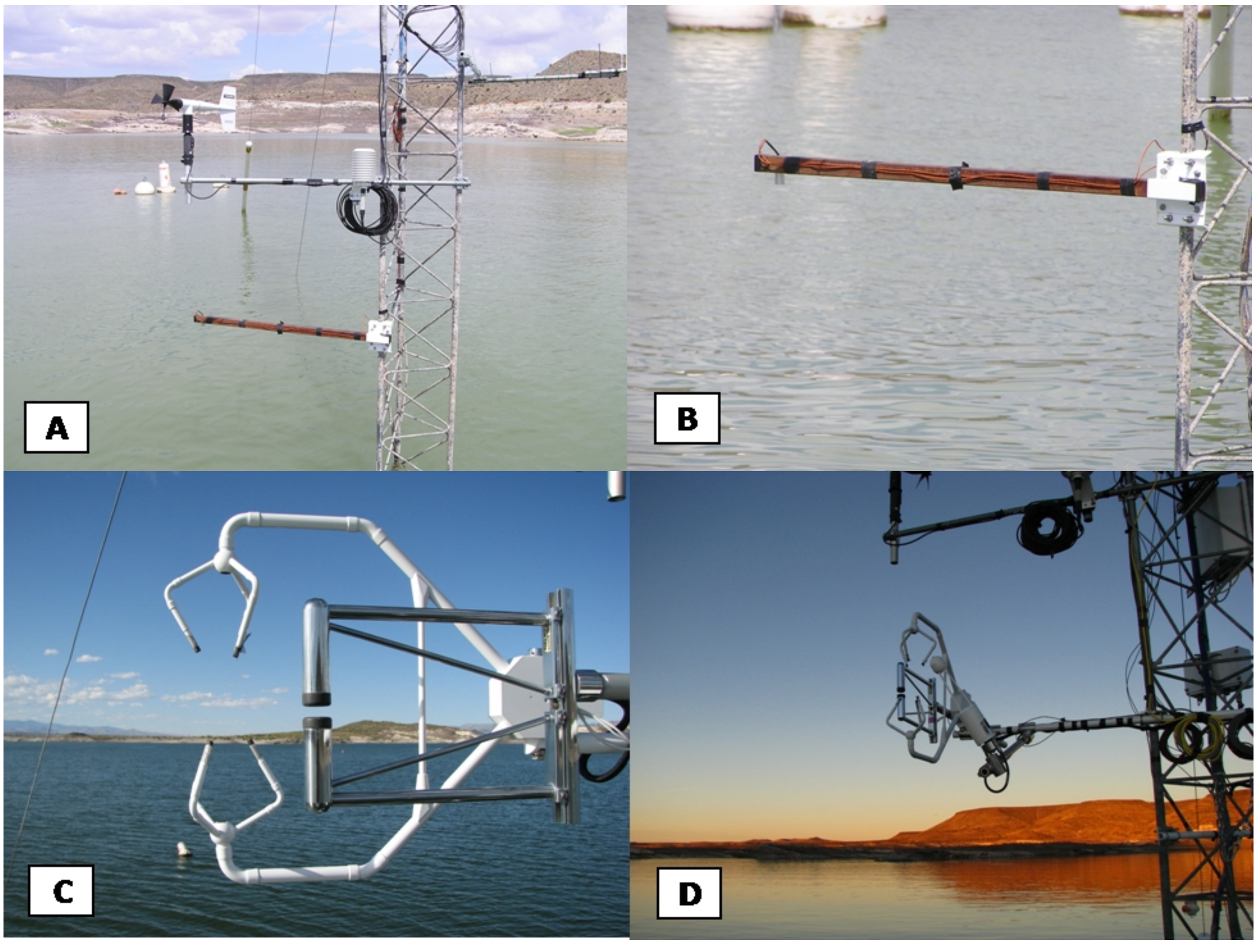


Figure 5. Evaporation comparison at Elephant Butte Reservoir on a daily basis

Appendix

Instrumentation used for measuring wind speed, air temperature and relative humidity (A) and water surface temperature (B). Eddy-covariance system used for measuring evaporation (close up view, B and D)



References

Arya, P. S. (2001). *Introduction of micrometeorology* - 2^{nd} edition. Academic Press, San Diego, California. International geophysics series, v. 79.

Brutsaert, W. (1982). *Evaporation into the atmosphere: Theory, history, and applications*. D. Reidel Publ. Co., Dordrecht, Netherlands.

Campbell Scientific, inc. (1998). *Eddy covariance system CA27 and KH20*, *Instruction manual.* Author, Logan, Utah.

Dingman, S. L. (2002). *Physical hydrology*. - 2^{nd} edition. Prentice-Hall., inc.: Upper Saddle River, New Jersey.

Gunaji, N. N. (1968). Evaporation investigations at Elephant Butte Reservoir in New Mexico. *Publications of the International Association d'Hydrologie Scientifique,* 78: 308-325.

Harbeck, G. E., Jr. (1962). A practical field technique for measuring reservoir evaporation utilizing mass-transfer theory. *Professional Papers of the U.S. Geological Survey,* 272-E:101-105.

Hicks, B.B. (1975). A procedure for the formulation of bulk transfer coefficients over water. *Boundary-Layer Meteorology*, 8, 515-524.

Horst, T. W. (1997). A simple formula for attenuation of eddy fluxes measured with first order response scalar sensors. *Boundary-Layer Meteorology*, 82, 219-233.

Jensen, M. D., Burman, R. D. and Allen, R. G., eds. (1990). *Evapotranspiration and irrigation water requirements: a manual*. American Society of Civil Engineers, New York, ASCE Manuals and Reports on Engineering Practice no.70.

Kondo, J. (1975). Air-sea bulk transfer coefficients in diabatic conditions. *Boundary-Layer Meteorology,* 9(1): 91-112.

Lee, X., Massman, W. and Law, B. (2004). *Handbook of micrometeorology: a guide for surface flux measurement and analysis.* Kluwer Academic Publishers, Dordrecht, the Netherlands. Atmospheric and oceanographic sciences library; v. 29.

Schotanus, P., Nieuwstadt, F. T. M. and De Bruin, H. A. R. (1983). Temperature measurements with a sonic anemometer and its application to heat and moisture fluctuations. *Boundary-Layer Meteorology*, 26(1): 81-93.

Stull, R.B. (1988). *An Introduction to Boundary Layer Meteorology.* Atmospheric Sciences Library, Kluwer Academic Publishers, Norwell, MA.

Tanner, C. B. and Thurtell, G. W. (1969). *Anemoclinometer measurements of Reynolds stress and heat transport in the atmospheric surface layer, final report*. United States Army Electronic Command, Atmospheric Sciences Laboratory, Fort Huachuca, Arizona.

Van Dijk, A., Kohsiek, W. and De Bruin, H. A. R. (2003). Oxygen sensitivity of krypton and Lyman-α hygrometers. *Journal of Atmospheric and Oceanic Technology,* 20(1): 143-151.

Webb, E. K., Pearman, G. I. and Leuning, R. (1980). Correction of flux measurements for density effects due to heat and water vapour transfer. *Quarterly Journal of the Royal Meteorological Society,* 106(447): 85-100.