# MEASURING AND ESTIMATING OPEN WATER EVAPORATION IN ELEPHANT BUTTE RESERVOIR IN NEW MEXICO

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## ABSTRACT

Elephant Butte Reservoir with an estimated surface area of 40,000 acres at full capacity is considered a major component of the Rio Grande hydrology. Understanding evaporative loss from the reservoir is needed for management and distribution of the Rio Grande water among various users. An eddy covariance tower is currently measuring the evaporation rate in a localized area of the reservoir. However, evaporation is highly variable across the Reservoir's water surface. This paper describes a methodology to account for spatial and temporal variability of the evaporation from reservoir using a combination of remote sensing and ground measurement.

## INTRODUCTION AND BACKGROUND

The Elephant Butte Reservoir (EBR) is a vital part of the management and distribution of water to southern New Mexico, Texas and Mexico. Increasing demand for water due to population growth coupled with recent drought has prompted water management agencies to determine better methods of assessing evaporation losses from the Reservoir. Currently, evaporation losses are estimated from a single evaporation pan placed near the dam at the southern end of the reservoir. This elevation can be significantly higher than the reservoir water surface, especially during periods of lower-than-average storage. Stage-surface-area tables developed from periodic hydrographic surveys are used to relate the point measurement of evaporation to the volume of water lost from the Reservoir. A mean annual rate of 9.74 ft/yr was reported by Farnsworth et al. (1982) from EBR's Class A pan evaporation data compiled from 1956 though 1970. However, evaporation studies performed on other deep relatively clear reservoirs in the western United States have found reservoir evaporation to be considerably less than pan evaporation and reference evapotranspiration (Allen and Tasumi, 2005). This is attributed to the large amounts of heat storage from solar radiation penetrating the water surface. The solar energy stored instantaneously as heat in the water body itself is not immediately available for the evaporation process. It is only available to the surface energy budget when transferred there by conduction or convection.

Remotely sensed surface temperature of the EBR Advanced Thermal Emission and Reflection Radiometer (ASTER) has shown the variability of surface temperature on spatial and temporal

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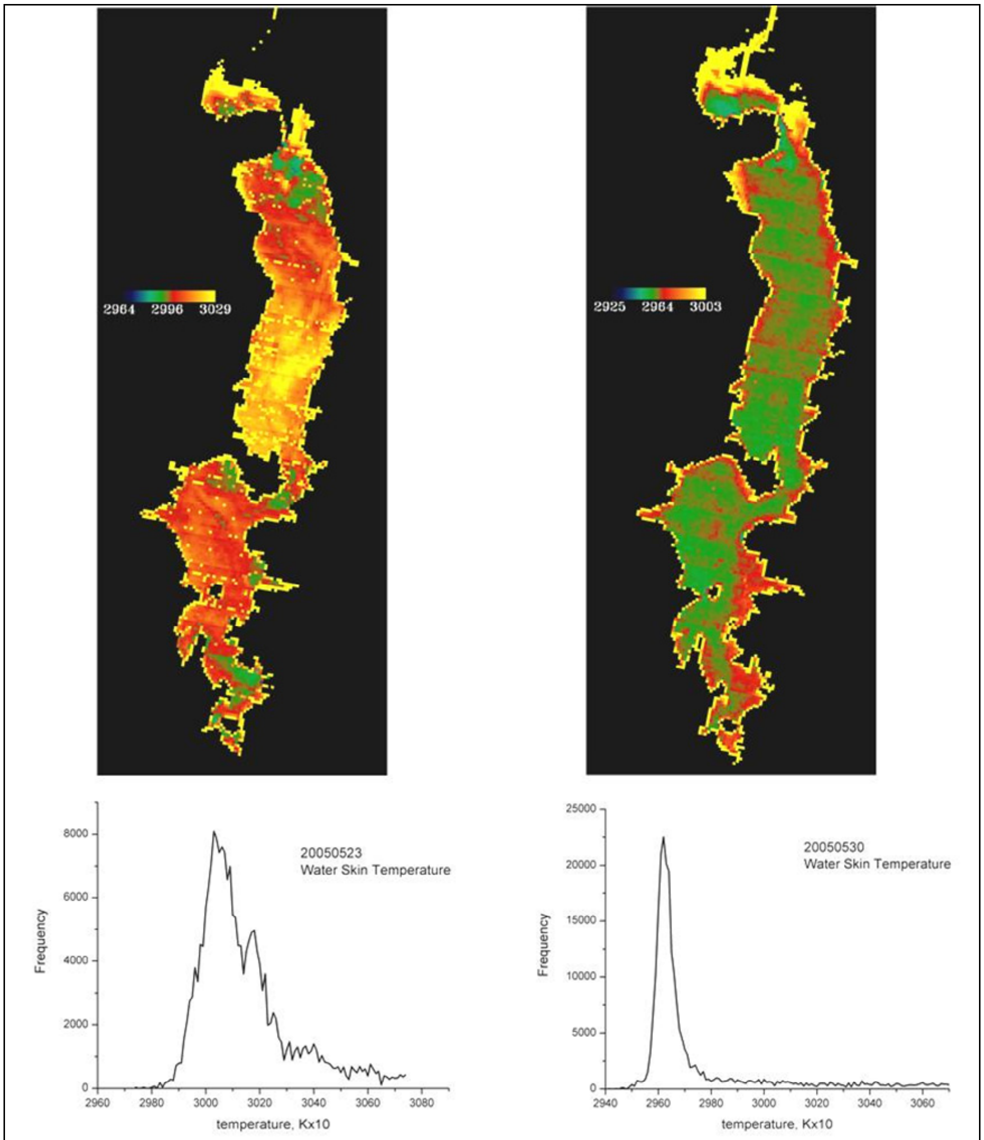
scale (figure 1). The image is color-coded to show variation in surface temperature (upper portion) while the graphs in the lower portion show the distribution of water temperature over the lake. This paper describes a methodology to account for spatial and temporal variability of the evaporation from reservoir using a combination of remote sensing and ground measurement.




A B

Figure 1. Satellite (ASTER) temperature results showing the spatial distribution of surface water temperature in (A) May 23 and (B) May 30 of 2005. The units of the scale are K x 10.

## Elephant Butte Reservoir Description and Location

The Elephant Butte Reservoir on the Rio Grande is located (Lat 33:09:15N; Long 107:11:28W, NAD27) in south central New Mexico. The reservoir was constructed from 1911 to 1916 with a capacity of 2,638,860 acre-ft in order to control downstream flooding, provide water for irrigation from the Rio Grande to the south valleys of Rincon and Mesilla, make deliveries to Texas and Mexico, and later for hydroelectric power generation. At full capacity, the reservoir extends to approximately 40 miles long and its width varies from 2 to 4 miles, covering a surface area of 40,000 acres (Scurlock, 1998). 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 a spillway of 4407 ft. The decrease in capacity was attributed to accumulation of sediments. A most recent unpublished report (U.S. Bureau of Reclamation, 2005) on storage and surface area stated that from January through December 2005 the reservoir storage ranged from 241,740 to 558,720 acre-ft, with corresponding surface areas of 8,673 and 13,748 acres at stages of 4309.94 and 4344.04 ft, respectively. It is considered normal for the reservoir stages to fluctuate 15 to 30 ft annually.

## Remotely Sensed Data

Surface temperature or skin temperature of the reservoir could be obtained with reasonable accuracy remotely e.g. satellite. For example, the ASTER five-channel multispectral thermal-infrared (TIR) scanner were compared to ground measurements of skin-temperature of water at Elephant Butte Reservoir in New Mexico. Skin temperature of water was measured using precision infrared sensor model IRTS-P (Apogee Instrument Inc., Logan, UT). The sensor was installed on an extended horizontal arm of approximately 1 m from an off-shore triangular tower in deep water (figure 2). The infrared sensor was maintained at an average height of less than 1 m above the water surface. Preliminary results indicated a good comparison. The comparison of "surface" measured skin temperature to satellite estimated surface temperature during the clear days of May 23$^{rd}$ and 30$^{th}$, 2005 show that ASTER under estimated skin temperature by only 0.31 K and 0.44 K, respectively.

## Ground measurements

A 115 ft off-shore tower using eddy covariance system (Campbell Scientific Inc., Logan, Utah) was installed in the reservoir to monitor fluxes. Micrometeorological sensors measuring wind velocity and direction, air temperature and relative humidity were also installed. Two basic weather stations located at the north and south ends of the Reservoir were used to collect land-based meteorological data such as ambient temperature, humidity, solar radiation, wind speed and direction, and precipitation.

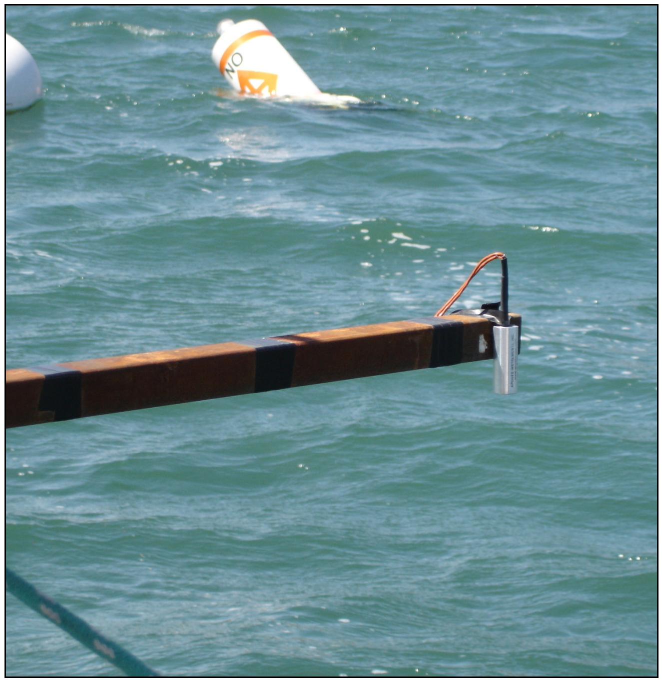


Figure 2. Infrared sensor model IRTS-P above water surface at Elephant Butte Reservoir

## METHODOLOGY

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, estimating evaporation losses over entire reservoirs is still a challenge. The bulk-aerodynamic method 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. 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 (Dingman, 2002). This is similar to the coefficients of heat and vapor transfer. This method is simple because it relies on relatively routine measurements of wind speed, air temperature, relative humidity, and water surface temperature. However, this method has been used for point measurements to estimate the entire water body surface. Using the same concept, the bulk-aerodynamic method combined with Monin-Obukhov stability function (Monteith and Unsworth, 1990) solved iteratively using ground and remotely sensed data, could be used to better estimate evaporation of the entire reservoir.

Assuming that the boundary layer over a smooth water surface is similar to that over a rough water surface, Kondo (1975) presented the following expressions of bulk-aerodynamic method for sensible and latent heat fluxes:

$$H = C_H \cdot c_p \cdot \rho_a \cdot u_z \cdot (T_s - T_a) \quad (3)$$

$$LE = C_E \cdot \lambda \cdot \rho_a \cdot u_z \cdot (q_{sat} - q_a) \quad (4)$$

Where,

| | | |
|---|---|---|
| $H$ | = | Sensible heat flux density [W/m$^2$] |
| $LE$ | = | Latent heat flux density [W/m$^2$] |
| $C_H$ | = | Bulk transfer coefficient for sensible heat |
| $C_E$ | = | Bulk transfer coefficient for latent heat |
| $c_p$ | = | Specific heat of air [J/g/°C] |
| $\lambda$ | = | Latent heat of vaporization of water [2450 J/g at 20°C] |
| $\rho_a$ | = | Density of air [g/m$^3$] |
| $u_z$ | = | Wind speed at z height above surface [m/s] |
| $T_s$ | = | Water surface temperature [°C] |
| $T_a$ | = | Air temperature [°C] |
| $q_{sat}$ | = | Saturated specific humidity at water-surface temperature [kg/kg] |
| $q_a$ | = | Specific humidity [kg/kg] |

In near neutral atmospheric conditions, Kondo (1975) stated that the bulk transfer coefficients would be calculated using the following empirical formulae:

$$C_H = \frac{k^2}{ln\left(\frac{z-d}{z_{om}}\right)\cdot ln\left(\frac{z-d}{z_{oh}}\right)} \tag{5}$$

$$C_E = \frac{k^2}{ln\left(\frac{z-d}{z_{om}}\right)\cdot ln\left(\frac{z-d}{z_{oq}}\right)} \tag{6}$$

Where,

| | | |
|---|---|---|
| $C_H$ | = | Bulk transfer coefficient for sensible heat |
| $C_E$ | = | Bulk transfer coefficient for latent heat |
| $k$ | = | von Karman's constant [0.41] |
| $z$ | = | Height of wind speed measurement [m] |
| $d$ | = | Zero plane displacement height [m] |
| $z_{om}$ | = | Surface roughness of momentum [m] |
| $z_{oh}$ | = | Surface roughness of sensible heat [m] |
| $z_{oq}$ | = | Surface roughness of latent heat [m] |

Kondo also proposed that $C_E$ can be explained by $C_H$ using the following relationship:

$$C_E = B \cdot C_H \tag{7}$$

Where, B is 1 for a wet surface and 0 (zero) for a dry surface

Therefore, $C_E \approx C_H$ over the water surface when the heights of sensible and latent heat are the same. Specific heat capacity of moist air is calculated using the empirical equation presented by Jensen et al. (1990), referencing Brutsaert (1982) as a function of specific humidity:

$$c_p = c_{pd} \cdot (1 + 0.84 \cdot q) \tag{8}$$

Where,

| | | |
|---|---|---|
| $C_p$ | = | *Heat capacity of air at constant pressure [J/g/°C]* |
| $c_{pd}$ | = | *Specific heat of dry air [1.005 J/g/°C]* |
| $q$ | = | *Specific humidity of air [kg/kg]* |

Expressing bulk transfer coefficient for sensible heat (Jensen et al., 1989; Allen and Tasumi, 2005):

$$C_H = \frac{1}{u_z \cdot r_h} \tag{9}$$

Where, $r_h$ is the aerodynamic resistance for heat transfer between the surface and elevation z. Therefore to calculate evaporation from lake surface, a relationship was developed between water surface temperature, Ts at the time of satellite overpass and temperature gradient, dT:

$$dT = T_s - T_a \tag{10}$$

Where dT is the near surface to air temperature difference ($T_s - T_a$). Assuming this relationship is linear, dT is expressed (Tasumi, 2003):

$$dT = aT_s + b \tag{11}$$

a and b coefficients. To calculate a and b, equation 3 was combined with Monin-Obukov stability function, and both equations were iteratively solved for dT, and $C_H$, using H values at two points, one off-shore point where the flux was measured and another dry spot on-shore. Using the two values for H, the coefficients a and b were developed for equation 11.

Once “a” and “b” were defined, H and $C_H$ for each pixel were calculated by combining equations 11, 3 and the Monin-Obukov function. Assuming $C_H$ is equal to $C_E$, equation 11, 10 and 4 were solved to determine dT, $T_a$ and LE for each pixel. Once LE flux (pixel x) for the time of satellite overpass was calculated, then the 24 hour evaporation values for each pixel (x) were estimated by multiplying the incident LE (x) values by the ratio of $LE_{24}/LE_i$ at the off-shore tower.

## RESULTS AND CONCLUSION

ASTER surface temperatures were available for December 22, 2001. Using the procedure described, evaporation rate was estimated for the Elephant Butte Reservoir. Figure 3a shows that there is a significant variability in the evaporation rate across the reservoir. The variability was caused by variation in water surface temperature, heat storage and probably wind velocity. In another study (in progress) flux is being measured at another point in the reservoir. This second point will be used to validate the procedure presented in the current paper. The variability of surface temperature (figure 3B) is analogous to spatial and temporal variation in reservoir evaporation.

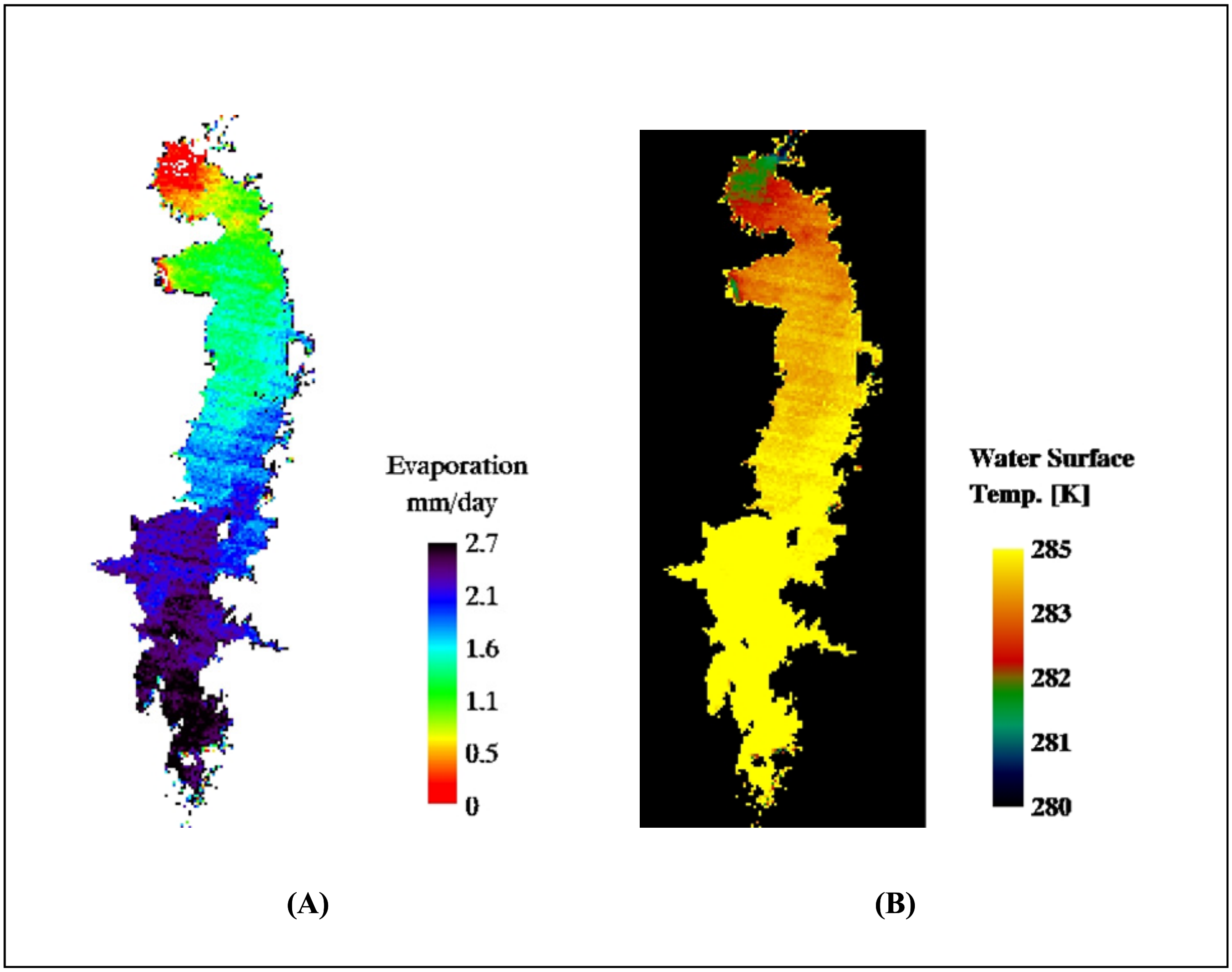



Figure 3. (A) Estimated evaporation rates and (B) surface water temperature at Elephant Butte Reservoir on December 22, 2001.

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