NM WRRI Student Water Research Grant Final Report

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2. Project title: Remote Sensing-Based Bulk-Aerodynamic Evaporation Depletion Model for Reservoir Management

3. Description of research problem and research objectives

The accurate estimation of evaporation from lakes and reservoirs is crucial for efficient water resource management. This is particularly true in areas where these water bodies support agriculture, municipal water supply, and power generation. Traditional in-situ methods, while reliable for small-scale measurements, often lack the spatial coverage required for larger and more complex reservoir water systems (Jiménez et al., 2018). This can lead to inaccurate assessments of overall evaporation rates (McCabe & Wood, 2006). To address this, we propose a novel approach that utilizes satellite technology, such as Landsat and MODIS missions, to provide pixel-level water surface temperature measurements across entire water bodies (Laraby, 2017). When combined with ground-level weather data, this technology can be used to determine evaporation depletion rates, providing a unique solution to the problem.

The objective of this proposed project is to utilize NASA's Landsat-9 satellite data along with ground-level weather data to estimate evaporation from Elephant Butte Reservoir on both spatial and temporal scales. The aim is to accurately determine the amount of evaporation from this significant reservoir located on the Rio Grande. Elephant Butte Reservoir supplies water for irrigating over 100,000 acres of agricultural land in southern central New Mexico, parts of Texas, and Mexico. The primary objective is to accurately calculate evaporation, thereby facilitating effective reservoir water management and potentially leading improvements in water resource management.

4. Description of methodology employed

4.1 Site description

Elephant Butte Reservoir (EBR), the largest reservoir on the Rio Grande in New Mexico, is located near the city of Truth or Consequences. The reservoir was formed by Elephant Butte Dam, a concrete gravity dam measuring 510 m in length and 93 m in height, including the spillway. The dam was constructed in 1916 and designed to regulate excess flows of the Rio Grande for irrigation supply to agricultural areas in the lower Rio Grande Valley of New Mexico and Texas. The initial storage capacity was approximately 2.64 million acre-feet (maf), but sediment deposition has reduced the effective capacity to about 2 million acre-feet (maf). At full capacity, EBR extends roughly 40 miles in a north to south orientation, with a variable width of 2 to 4 miles and an irregular shoreline (Scurlock, 1998). During the study period, reservoir storage levels varied considerably. In 2022, the reservoir storage capacity ranged from 73,855 to 265,222 acre-feet and in 2023, it ranged from 227,459 to 340,240 acre-feet. The location of the Elephant Butte reservoir, the energy flux measurements stations and weather stations summarized in Table 1.

Table 1. Onshore and offshore measurement stations at Elephant Butte Reservoir, including their names, locations, and elevations. Latitude, longitude, and elevation values are referenced to the World Geodetic System (WGS84).

Station Name	Latitude	Longitude	Elevation (ft)
Elephant Butte Reservoir	N33° 09′ 15.00″	W107° 11′ 32.50″	-
Elephant Butte Eddy Covariance flux station (EB-1), *offshore*	N 33° 13' 32.00"	W 107° 09' 40.00"	4336
Elephant Butte Bulk-Aerodynamic flux station (EB-2), *onshore/offshore*	N 33° 13' 34.88"	W 107° 09' 30.43"	4386
North Lake climate station (Nlake), *onshore*	N 33° 17' 50.14"	W 107° 11' 37.88"	4504
South Lake climate station (Slake), *onshore*	N 33° 08' 45.52"	W 107° 11' 03.44"	4576

4.2 Instrumentation Set up at Elephant Butte Reservoir

4.2.1 Elephant Butte Eddy Covariance flux station (EB-1)

Eddy covariance instrumentation was installed on an offshore 74-ft triangulated tower (EB-1) (Figure 1). The tower, supported by a concrete base and guy wires anchored securely, was designed to have a minimal footprint to reduce turbulence effects and ensure sensor stability. The site provided adequate fetch for evaporation measurements, with prevailing winds mostly blowing across the reservoir from the north and south to southwest. The location was chosen for its accessibility by boat, low boating traffic, and suitability for routine maintenance. Water depth at EB-1 varied seasonally, ranging from 0.5 to 25 ft in 2022 and 24 to 40 ft in 2023, monitored every 30 minutes using a CS451 pressure transducer (Campbell Scientific Inc., Logan, UT).

Meteorological sensors included a wind monitor (Model 05103) for wind speed and direction, an air temperature and relative humidity probe (Model HMP155A), and an infrared radiometer (Model SI-111) for water skin temperature. Data from these sensors were collected at a rate of one sample every 10 seconds and averaged every 30 minutes using a CR1000X datalogger. The station was serviced and maintained biweekly. All the instrumentations were purchased from Campbell Scientific Inc., Logan, Utah. These data supported in-situ bulk-aerodynamic evaporation calculations at EBR.

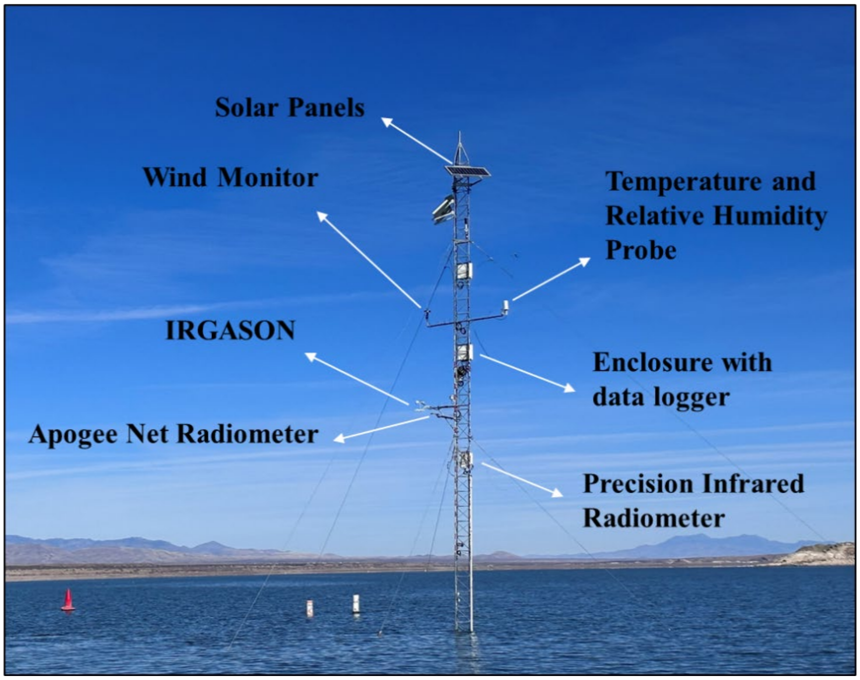

Figure 1. Instrument setup showing sensors at the Elephant Butte Eddy Covariance flux station (EB-1) at Elephant Butte Reservoir.

4.2.1 Elephant Bulk-Aerodynamic flux station (EB-2)

The EB-2 Bulk-Aerodynamic flux station was installed on a 30-ft triangulated tower (Figure 2) as a long-term replacement for EB-1 and as a safeguard for continued data collection in the event of higher reservoir levels. Instrumentation included wind sensors and air temperature/relative humidity probes installed at two different heights, a pyranometer for global shortwave radiation, a rain gauge for precipitation, and a barometer for atmospheric pressure. Measurements were sampled every 10 seconds, averaged to 30-minute intervals, and the data were collected using a CR3000 datalogger powered by solar panels and batteries. The station was serviced and maintained biweekly.

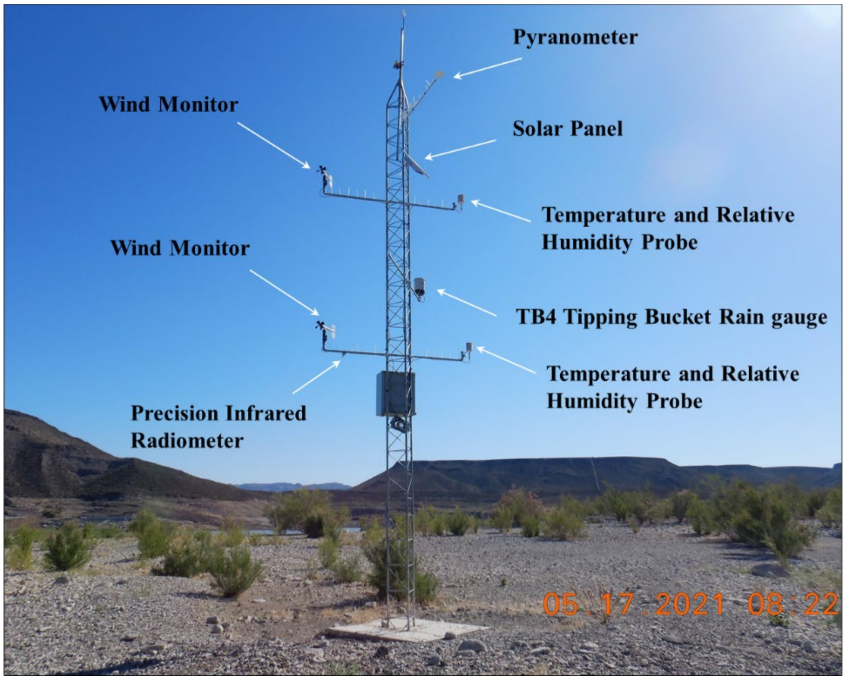

Figure 2. Instrument setup of the Elephant Butte Bulk-Aerodynamic flux station (EB-2) at Elephant Butte Reservoir.

4.3 Bulk-Aerodynamic (B_AER) Method

The bulk aerodynamic method is commonly applied to estimate sensible and latent heat fluxes over open water bodies (Brutsaert, 1982). This approach is based on mass transfer theory, which explains that heat and water vapor move from regions of higher concentration to regions of lower concentration at rates proportional to the concentration gradients. In practice, the rate of vapor transfer is primarily controlled by the near-surface humidity gradient and wind speed. Despite its simplifications, the bulk aerodynamic method remains a practical and reliable approach for quantifying evaporation from free water surfaces because it requires only routinely available meteorological inputs such as wind speed, air temperature, relative humidity, and water surface temperature (Singh & Xu, 1997). 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 latent heat fluxes in the B_AER method (Hicks, 1975)

$$\mathrm{LE} = \mathrm{C_E}.\lambda.\rho_\mathrm{a}.\mathrm{U_{10.}}(\mathrm{q_{sat}} - \mathrm{q_a})$$

where, LE is latent heat flux density (W/m^2), $\mathrm{C_E}$ is bulk transfer coefficient for latent heat, λ is latent heat of vaporization of water (J/g), ρ_a is density of air (g/m^3), $\mathrm{U_{10}}$ is wind speed at 10 m height above the water surface (m/s), $\mathrm{q_{sat}}$ is saturated specific humidity at the water surface (kg/kg), and $\mathrm{q_a}$ is specific humidity (kg/kg) of the air.

4.4 Model development

Two years (2022–2023) of meteorological data were collected and processed at 30-minute and daily intervals. The dataset included air temperature, relative humidity, wind speed and direction, water surface temperature, solar radiation, and barometric pressure, measured from EB-1 and EB-2 stations. These variables were used as inputs to the bulk-aerodynamic method for reservoir evaporation estimation.

Landsat-8 and Landsat-9 satellite images of the reservoir during clear skies were obtained from the USGS Earth Explorer. The meteorological data, including air temperature, relative humidity, wind speed, and atmospheric pressure, were collected from a nearby weather station (EB-2) at the same times as the image acquisition. Water body delineation was performed using the Modified Normalized Difference Water Index (MNDWI) with Python. The MNDWI was used to distinguish the reservoir surface from surrounding land areas, effectively isolating the water body for analysis.

Water surface temperature (WST) was derived for each 30 m × 30 m pixel of the reservoir from the satellite imagery. To validate and correct these estimates, in situ WST measurements from the EB-1 eddy covariance station were used as the reference. For comparison, WST values were averaged over a 3 × 3-pixel grid (90 m × 90 m) near the EB-1 location. A linear regression analysis was then conducted between the satellite-derived and EB-1 in situ WST values. Where discrepancies were identified, regression-based correction factors were applied to adjust the satellite-derived WST, to reduce bias and improve accuracy. The corrected WST values, together with corresponding meteorological variables (EB-2), were incorporated into the bulk-aerodynamic method of pixel-wise evaporation estimation across the reservoir surface. The satellite-based evaporation estimates were then validated against in situ evaporation measurements from the EB-1 stations. Model performance was evaluated using statistical metrics including Root Mean Square Error (RMSE), Mean Absolute Error (MAE), and Nash-Sutcliffe Efficiency (NSE).

5. Description of results; include findings, conclusions, and recommendations for further research

5.1 Validation of Satellite-Derived Water Surface Temperature

To evaluate the accuracy of WST, a comparison was conducted between in situ measurements at the EB-1 station and the average of a 3 × 3-pixel grid (90 m × 90 m) near EB-1 location. Data from 2022 and 2023 were analyzed, covering 72 clear-sky overpass days. Measured WST ranged from 4.24 °C to 29.39 °C, while satellite-derived WST ranged from 5.99 °C to 34.90 °C. Across all observations, satellite-derived temperatures consistently overestimated in situ measurements. The higher biases occurred during warmer months, where satellite retrievals were systematically higher than in situ values.

A regression analysis (Figure 3) confirmed a strong linear relationship between the two datasets ($R^2 = 0.987$, SEE = 0.83 °C). However, the slope of 0.85 indicates that satellite-derived water surface temperatures generally overestimate in situ measurements, particularly at higher temperature ranges. This bias was corrected by applying regression-based adjustment factors, thereby aligning satellite-derived WST with EB-1 measurements and improving input reliability for the bulk aerodynamic evaporation model. These findings demonstrate that while raw satellite WST provide useful spatial coverage, validation and correction using in situ data are essential to reduce bias and ensure accurate estimation of evaporation from Elephant Butte Reservoir.

Spatial distributions of instantaneous WST for Elephant Butte Reservoir are shown in Figure 4. Each map represents a single clear-sky Landsat overpass day for one month in 2022, illustrating the spatial variability of WST captured during those specific overpass times. Average reservoir ranged from 5.1 °C in February to 27.8 °C in August, reflecting the strong seasonal cycle. Warmer months exhibited higher spatial variations, whereas cooler months showed lower temperatures with less variation across the reservoir.

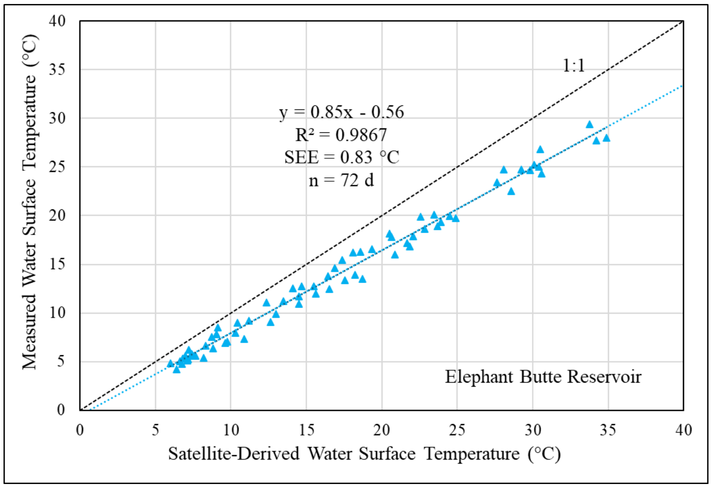

Figure 3. Comparison between satellite-derived and measured water surface temperature at Elephant Butte (EBR) for 2022 and 2023.

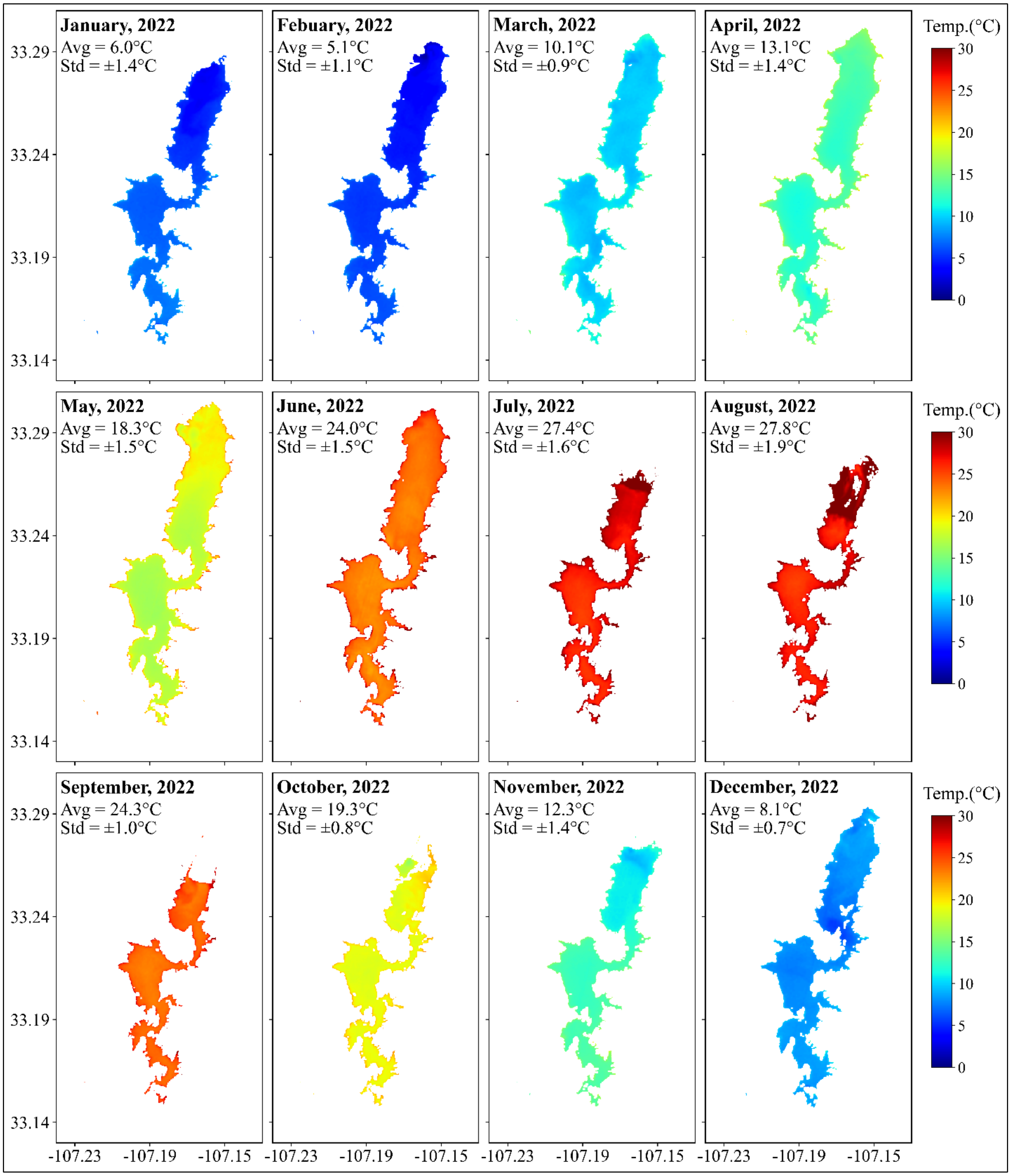

Figure 4. A sample image from each month showing the instantaneous spatial and temporal distribution of corrected satellite-derived water surface temperatures at Elephant Butte Reservoir (EBR) for 2022. Avg and Std represent the average and standard deviation of the water surface temperature of all pixels in each image, respectively.

5.2 Satellite-Derived Evaporation Estimates

To evaluate the performance of the remote sensing-based bulk-aerodynamic model, satellite-derived instantaneous evaporation was compared with in situ measurements from the EB-1 station. The comparison covered clear-sky Landsat overpass days in 2022 and 2023. Figure 5 presents the time series of measured and satellite-derived instantaneous evaporation. The two datasets showed strong agreement, with the satellite-based estimates closely tracking observed values across both seasonal cycles and short-term fluctuations. The model successfully captured the timing and magnitude of peak evaporation events, particularly during spring and summer months. Statistical evaluation indicated the $R^2 = 0.93$, RMSE = 0.017 mm, MAE = 0.011 mm and NSE = 0.93. According to the performance ratings proposed by Moriasi et al. (2007), an NSE greater than 0.90 reflects *"very good"* model performance, confirming the reliability of the satellite-based approach.

Spatial patterns of instantaneous evaporation across Elephant Butte Reservoir are shown in Figure 6 for one clear-sky overpass day per month in 2022. These maps demonstrate that evaporation variability was strongly influenced by the distribution of surface temperatures. Maximum average evaporation occurred in August (0.143 mm), corresponding to peak summer WST, while minimum values (approximately 0.02 mm) were observed during the winter months. Seasonal shifts were clearly reflected in the spatial evaporation patterns.

Overall, the results confirm that the satellite-based bulk-aerodynamic model effectively reproduces both the temporal and spatial variability of reservoir instantaneous evaporation when validated against ground-based flux measurements.

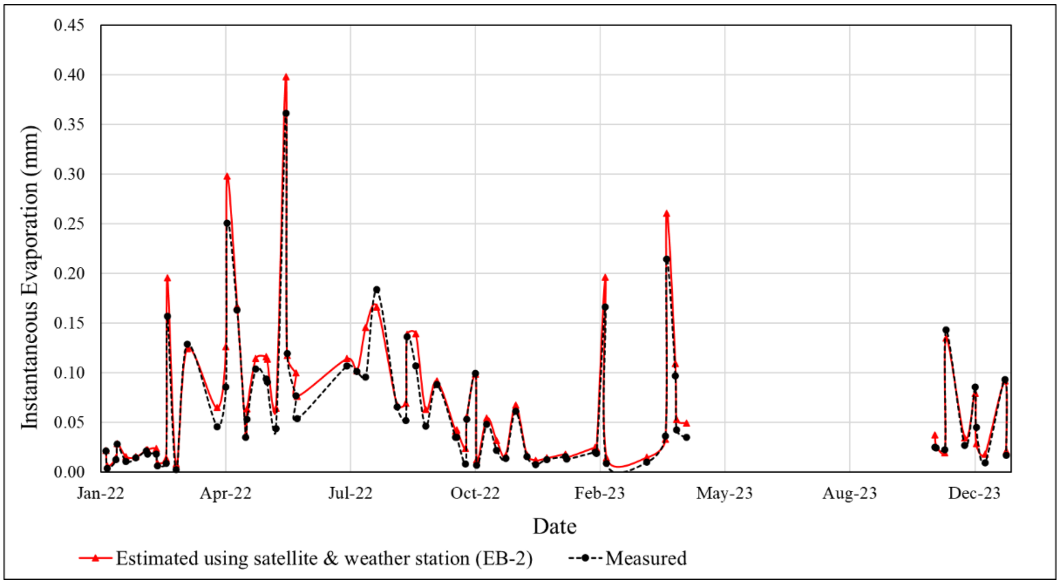

Figure 5. Time series plot of satellite-derived and measured instantaneous evaporation for Elephant Butte (EBR) for 2022 and 2023.

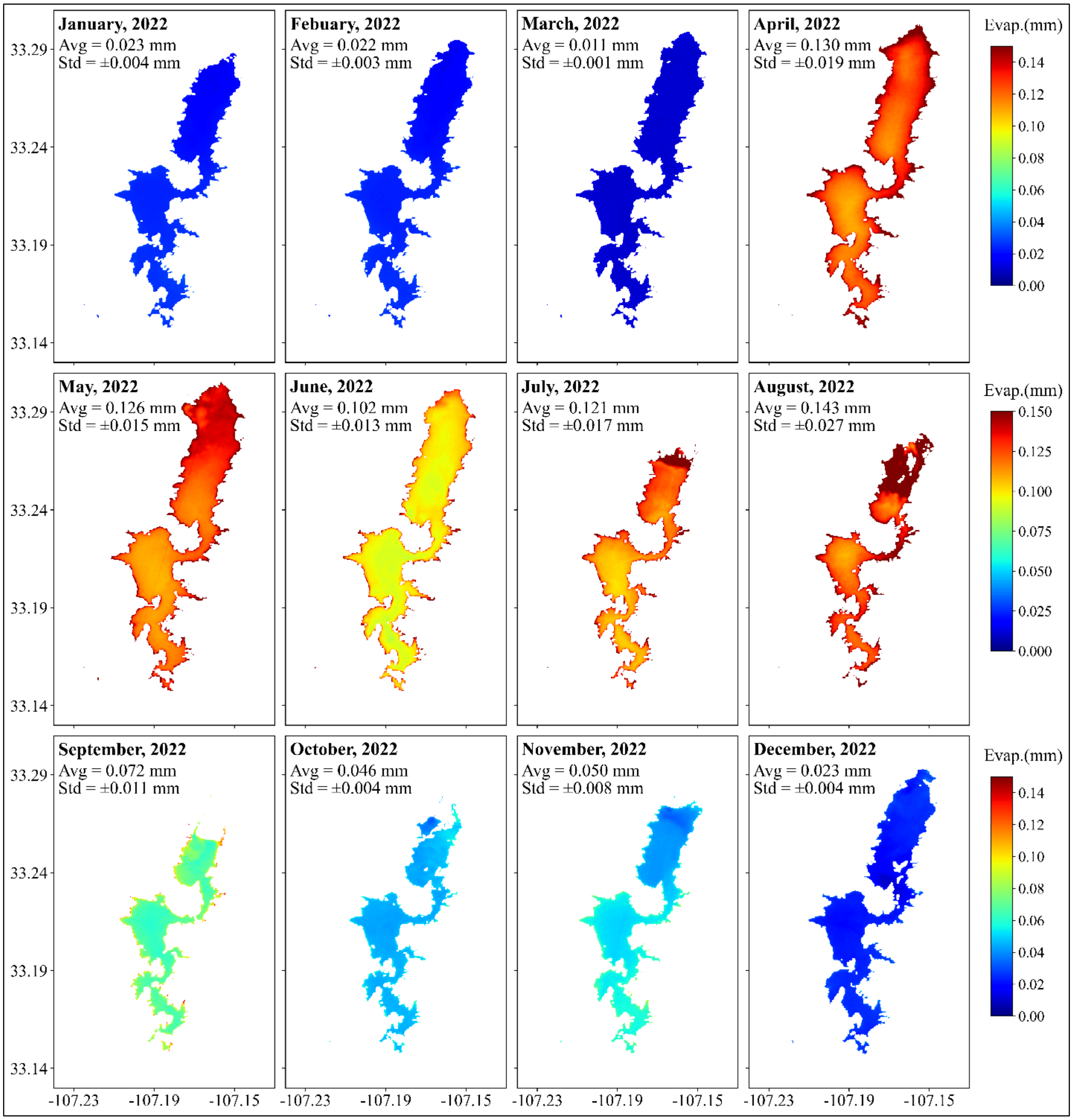

Figure 6. A sample image from each month showing the instantaneous spatial and temporal distribution of evaporation at Elephant Butte Reservoir (EBR) for 2022. Avg and Std represent the average and standard deviation of the water surface temperature of all pixels in each image, respectively.

6. Conclusion

This study showed that integrating meteorological data from the EB-2 flux/weather station with satellite-derived water surface temperatures provides accurate and reliable estimates of reservoir instantaneous evaporation. The satellite-based bulk-aerodynamic model reproduced both the temporal dynamics and spatial variability of evaporation when validated against in situ measurements from EB-1. The agreement between satellite imagery, ground-based weather data, and in situ flux observations confirms the model's capability to predict reservoir evaporation with very good performance. This approach offers a scalable and efficient tool for monitoring evaporation in large reservoirs, supporting improved water resource management in semi-arid regions.

7. Provide a paragraph on who will benefit from your research results. Include any water agency that could use your results.

This research will benefit water management agencies, such as the U.S. Bureau of Reclamation, the Elephant Butte Irrigation District (EBID), and El Paso County Water Improvement District No. 1 (EPCWID1), as well as farmers in the region who rely on consistent water deliveries for crop production. The spatially detailed evaporation estimates can support more effective water release planning, optimize irrigation scheduling, and ensure equitable water distribution across the U.S.–Mexico border. This approach offers a cost-effective tool for monitoring reservoir evaporation, enhancing water conservation, and management in arid regions.

8. Describe how you have spent your grant funds. Also provide your budget balance and how you will use any remaining funds. If you anticipate any funds remaining after September 30, 2025, please contact Carolina Mijares immediately (575-646-7991; mijares@nmsu.edu).

i. Total grant funded: **$ 7,502**
ii. Expenditures:
    a. Travel expenses for the 69th Annual New Mexico Water Conference - $615.27
    b. Field visit expense to maintain the research sites - $393.90
    c. Cellphone renewal for remote data collection - $288.00
    d. Graduate student health insurance - $600
    e. Fringe Benefits - $27.00
    f. graduate student's summer salary - $5,568.18
    g. Remaining Balance - $9.65

9. List presentations you have made related to the project.

i. Presented a poster at the ***69th Annual New Mexico Water Conference*** hosted by WRRI on November 5-6, 2024, at Buffalo Thunder Hilton Resort, Santa Fe, New Mexico.

ii. Presented a poster at the ***Graduate Research & Arts Symposium (GRAS) 2025***, hosted by the NMSU Graduate Student Council on April 24, 2025, at Corbett Center, New Mexico State University, Las Cruces, NM.

10. List publications or reports, if any, that you are preparing. For all publications/reports and posters resulting from this award, please attribute the funding to NM WRRI and the New Mexico State Legislature by including the account number: NMWRRI-SG-FALL2024.

None at this point

11. List any other students or faculty members who have assisted you with your project.

Faculty: Dr. A. Salim Bawazir

12. Provide special recognition awards or notable achievements as a result of the research including any publicity such as newspaper articles, or similar.

None

13. Provide information on degree completion and future career plans. Funding for student grants comes from the New Mexico Legislature and legislators are interested in whether recipients of these grants go on to complete academic degrees and work in a water-related field in New Mexico or elsewhere.

Currently working on my PhD in Civil Engineering with a focus on Water Resources.

References

1. Brutsaert, W. (1982). Evaporation into the atmosphere: Theory, history, and applications. Springer. https://doi.org/10.1007/978-94-017-1497-6.

2. Hicks, B. B. (1975). A procedure for the formulation of bulk transfer coefficients over water. Boundary-Layer Meteorology, 8(3-4), 515-524.

3. Jiménez, C., Martens, B., Miralles, D. M., Fisher, J. B., Beck, H. E., & Fernández-Prieto, D. (2018). Exploring the merging of the global land evaporation WACMOS-ET products based on local tower measurements. *Hydrology and Earth System Sciences*, *22*(8), 4513-4533.

4. Laraby, K. (2017). *Landsat surface temperature product: global validation and uncertainty estimation*. Rochester Institute of Technology.

5. McCabe, M. F., & Wood, E. F. (2006). Scale influences on the remote estimation of evapotranspiration using multiple satellite sensors. *Remote Sensing of Environment*, *105*(4), 271-285.
6. Moriasi, D. N., Arnold, J. G., Van Liew, M. W., Bingner, R. L., Harmel, R. D., & Veith, T. L. (2007). Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. *Transactions of the ASABE*, *50*(3), 885-900.
7. Scurlock, D. (1998). *From the rio to the sierra: An environmental history of the Middle Rio Grande Basin*. US Department of Agriculture, Forest Service, Rocky Mountain Research Station.
8. Singh, V. P., Xu, C. Y. (1997). Evaluation and generalization of 13 mass-transfer equations for determining free water evaporation. Hydrological Processes, 11(3), 311-323.