Estimating Open-Water Evaporation from Elephant Butte Reservoir using the Weather, Research, and Forecasting Model

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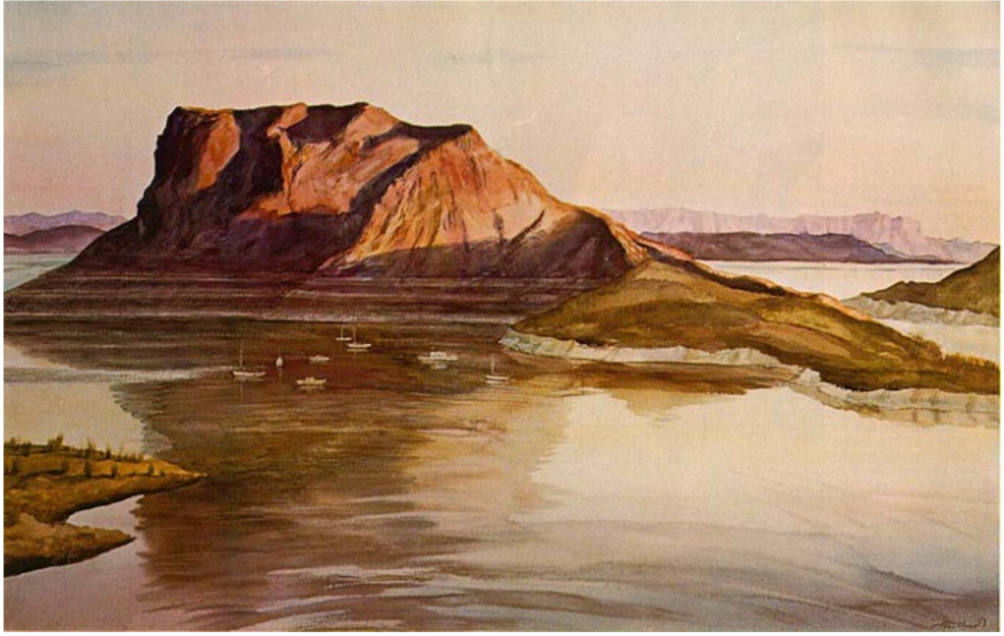

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14. ABSTRACT

In this study, we utilize the WRF model coupled to a 1-D energy-balance lake model, WRF-Lake, to simulate evaporation across Elephant Butte Reservoir between February 1994 through January 1996. We focus on Elephant Butte Reservoir because it is vital to water deliveries among US states and to Mexico and is currently the focus of multiple in-situ evaporation studies. We develop spatial estimates of evaporation across the reservoir surface during a period in which reservoir levels were high and fairly stable and compare simulated results with those estimated from three alternative datasets valid over the same historical time period. Those datasets include Class A pan records, output from the Complementary Relationship Lake Evaporation (CRLE) model forced with meteorological conditions from the WRF model, and output from the Global Lake Evaporation Volume (GLEV) dataset.

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Acronyms

CFSR	Climate Forecast System Reanalysis
CRLE	Complementary Relationship Lake Evaporation model
d01	Domain 1
d02	Domain 2
d03	Domain 3
DOI	Department of Interior
EBR	Elephant Butte Reservoir, NM
GLEV	Global Lake Evaporation Volume dataset
HPC	High-Performance Computing
TSC	Technical Service Center
USGS	United States Geological Survey
WRF	Weather, Research, and Forecasting model
WRF-Lake	Weather, Research, and Forecasting Lake model

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Executive Summary

Estimates of reservoir evaporation are needed for a variety of Reclamation activities, including water supply and demand planning, water storage and accounting policies, deliveries under interstate water compacts and international treaties, and climate impact assessment studies. Although necessary for a variety of applications, accurate estimates of evaporation rates and volumes can be difficult and/or expensive to obtain.

At Elephant Butte Reservoir, along the Rio Grande in south-central New Mexico, evaporation represents a major loss of water from the reservoir and counts as a loss against the state of New Mexico's annual water allocation under the Rio Grande Compact. Current evaporation estimates from the reservoir are based on a Class A evaporation pan located over land on the south side of the reservoir, a method with documented inaccuracies in representing lake or reservoir evaporation. Given the importance of this variable for operations and decision-making, Reclamation has and continues to fund studies employing a variety of technologies to estimate evaporative losses from Elephant Butte Reservoir. These studies are designed to build toward a better understanding of both loss rates from the reservoir at particular locations and total volumes of water lost to evaporation from the reservoir.

In this study, we utilize the WRF model coupled to a 1-D energy-balance lake model, WRF-Lake, to simulate evaporation across Elephant Butte Reservoir. We focus on Elephant Butte Reservoir because it is vital to water deliveries among US states and to Mexico and is currently the focus of multiple in-situ evaporation studies. Through our modeling efforts, we calibrate WRF-Lake and develop spatial estimates of evaporation across the reservoir surface during a period in which reservoir levels were high and fairly stable, between February 1994 through January 1996.

In order to better understand evaporation estimates from the coupled WRF/WRF-Lake method, we compare simulated reservoir-averaged evaporation totals with those estimated from three alternative datasets valid over the same historical time period. Those datasets include Class A pan records, output from the Complementary Relationship Lake Evaporation (CRLE) model forced with meteorological conditions from the WRF model, and output from the Global Lake Evaporation Volume (GLEV) dataset. Results from the coupled WRF/WRF-Lake method compared favorably among other reservoir-average estimates. However, the real advantage of this method is its ability to characterize variations in evaporative loss rates across the reservoir, and in doing so, to be able to generate an estimate of the total volume of water lost from the reservoir, a key parameter in our water budgets, on a monthly or annual timescale. Total volumetric evaporative losses from the coupled WRF/WRF-Lake method were approximately 172000 and 177000 acre-ft during the first and second years of simulation, respectively.

Study partners, both internal and external to Reclamation, played a critical role in the success of this project. Results and technical tools will be used to support future WRF/WRF-Lake studies. This project has also produced benefits related to management and operations, technical capacity within the TSC and Reclamation more broadly, and lessons learned about the benefits of this approach, as well as the data and computational requirements.

1 Introduction

1.1 Background

Evaporation is an important physical process that directly links the water and energy budgets of any inland water body. In arid regions of the western United States, evaporation can represent the greatest (natural) source of water loss to a system's water budget and can exacerbate water challenges in systems with variable and/or limited water supply. Thus, quantifying, understanding, and predicting evaporation are critical to water supply, water operations, and water rights issues.

At the Bureau of Reclamation (Reclamation), estimates of reservoir evaporation are used in a variety of activities, including water supply and demand planning, water storage and accounting policies, deliveries in accordance with interstate water compacts, and climate impact assessment studies (SECURE Water Act PL-111-11, section 9503). There is no standard methodology in use across the agency to quantify evaporative losses from reservoirs; staff in area and regional offices may apply the method(s) they deem most appropriate for their region. In the absence of official guidelines, many Reclamation offices utilize estimates of evaporation from Class A pans in water accounting computations. Class A pans are commonly used to estimate evaporation because of their ease of use, low costs of operation and maintenance, and long, consistent records. However, studies suggest that Class A pans are one of the least accurate methods for estimating reservoir evaporation (Friedrich et al. 2018; Collison 2019). There are many alternative methods available to estimate open-water evaporation, including the bulk-aerodynamic method, water or energy budgets, the eddy covariance approach, Bowen ratio approach, and others. Most methods have known advantages and disadvantages, which are summarized in Table 1 of Friedrich et al. (2018).

Elephant Butte Reservoir, located along the Rio Grande in south-central New Mexico (EBR; Figure 1.1), the principal storage facility of Reclamation's Rio Grande Project, provides water for irrigation, municipal use, recreation, flood storage, international water deliveries, and hydroelectric generation. Elephant Butte Dam also serves as the water delivery point from New Mexico to Texas under the Rio Grande Compact, making the loss rates from this reservoir a critical component of Compact accounting. A large surface area when the reservoir is full, and an arid climate make evaporative losses from EBR a major source of water loss to the overall hydrologic budget of the Upper Rio Grande (Moreno 2008). Official evaporation estimates used in the Upper

Rio Grande Water Operations Model are based on measurements from a single Class A evaporation pan located at the southern end of the reservoir (Moreno 2008), which provides a consistent, but likely inaccurate, record of evaporation losses from this reservoir over time.

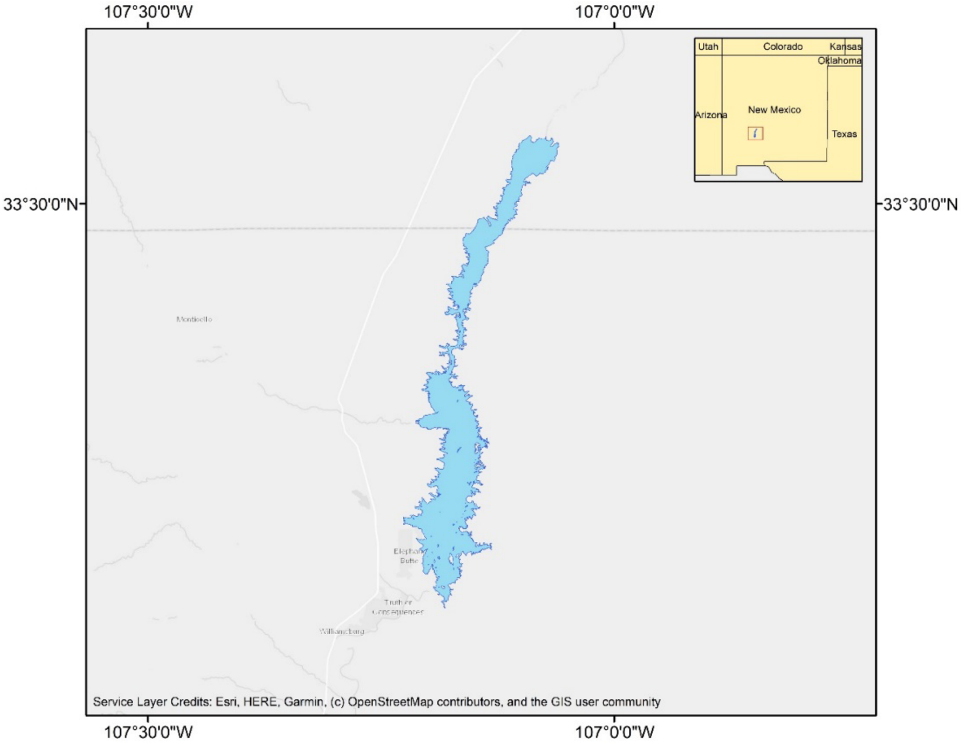

Figure 1.1 – Location of Elephant Butte Reservoir, NM.

Given the importance of water in EBR to Reclamation project operations, an interstate water compact, and international decrees, a number of studies have and continue to estimate evaporative losses from EBR using different methods. Gunaji (1968) quantified evaporative losses from EBR using an energy budget approach and mass transfer technique. The intent of that study was to develop baseline evaporation numbers in support of evaporation suppression investigations. More recently, many studies have employed eddy covariance (EC) systems and bulk mass transfer techniques. For example, Bawazir and King (2003) used a bulk aerodynamic approach, Bowen ratio energy approach, and eddy covariance (EC) system to estimate evaporation from EBR between 2001 and 2002. Similarly, Moreno et al. (2008) estimated evaporation from EBR using bulk aerodynamic and EC methods between 2006 and 2007. Other (point) in-situ studies currently underway in the region include a Collison Floating Evaporation Pan project led by Dr. Jake Collison, a research assistant professor from the University of New Mexico, and supported by the

Reclamation's Upper Colorado River Operations group and two deployed EC towers led by Dr. Salim Bawazir, an assistant professor from New Mexico State University, and supported by the Research and Development Office's Science and Technology (S&T) Program.

While point, in-situ methods are crucial for quantifying evaporation, understanding over-lake conditions, and validating alternative estimates, the methods alone do not provide information on the spatial heterogeneity of evaporation across the surface of a water body. To combat this limitation, Bawazir et al. (2007) used in-situ evaporation observations from an EC tower in conjunction with remotely sensed water skin temperature to estimate evaporative losses across EBR on December 22, 2001. Their results are shown in Figure 1.2. The current S&T project led by Dr. Bawazir will explore additional means by which to use remotely sensed water surface temperature to estimate evaporation across EBR. Some limitations of remotely sensed approaches include image contamination, limited overpass frequency, and coarse spatial and temporal resolutions.

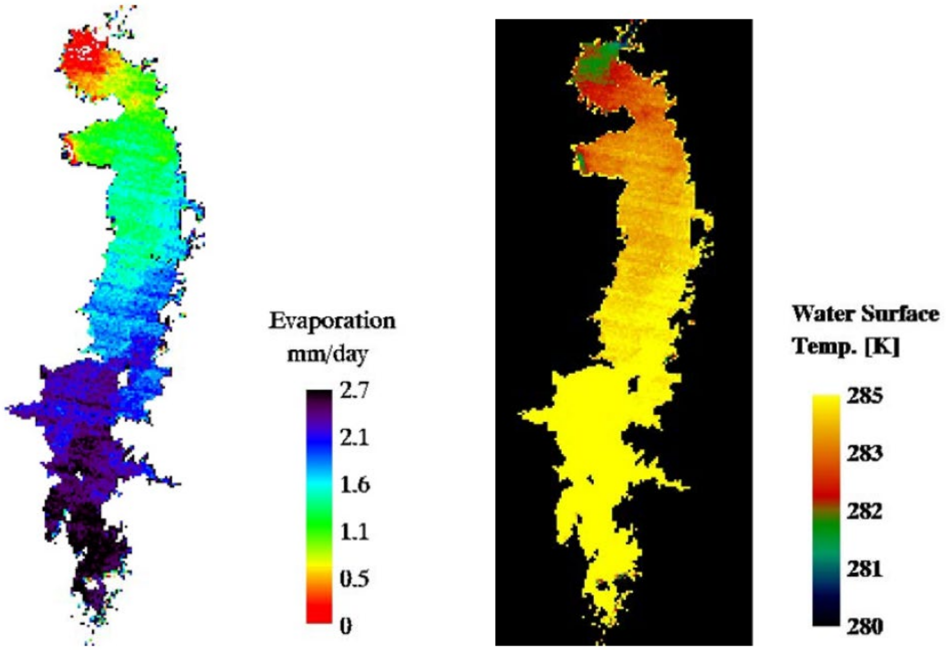

Figure 1.2 – (left) Daily evaporation totals (mm/day) and (right) water surface temperature (K) across Elephant Butte Reservoir on December 22, 2001. Figure from Bawazir et al. (2007).

One method to estimate open-water evaporation that combats limitations associated with remotely sensed data and has not previously been tested within Reclamation is the use of a numerical weather prediction model coupled to a lake model to estimate total spatial variability in evaporation rates across a reservoir, and total volumetric water losses to evaporation. This approach has been used within the scientific community to estimate water surface temperatures and ultimately evaporation totals from other reservoirs around the globe. For example, Xu et al. (2016) simulated sensible and latent heat fluxes (i.e., evaporation) across a small inland water body (~250 km^2) freshwater inland lake, Erhai Lake, in southwestern China, using the same modeling approach. The authors presented results from a one-year simulation, showing favorable comparisons with EC evaporation rates estimates from a platform located 80 m from shore.

1.2 Objectives

Reclamation has been spending hundreds of thousands of dollars on in-situ, eddy covariance evaporation studies across the West (e.g., Lake Powell, AZ, Clear Lake, CA, etc.). While these projects record observations that are invaluable for benchmarking evaporative loss rates, the costs associated with these projects are extremely high, and the studies produce site-specific estimates of evaporative loss rate, not total water volumes lost to evaporation from each reservoir. To develop evaporation estimates from a different reservoir using the same in-situ eddy covariance methodology, equipment must be transferred, installed at the new location, and recalibrated. Further, Mahrer and Assouline (1993) argued that in regions of complex topography, point records of evaporation from an eddy covariance system should not be extrapolated across lake surfaces due to heterogeneity in water column depth, heat storage, and surface winds, among other variables, suggesting a clear limitation of this in-situ method.

On the contrary, a coupled numerical model can be used to estimate reservoir evaporation at any reservoir that is large enough to be represented at the scale of a numerical weather model. Implementing a coupled numerical weather modeling framework allows for the quantification of evaporation *across* the reservoir at time scales ranging from hours to days, without the need to extrapolate point totals. These tools can also be used to understand how a given lake or reservoir may respond to alternative forcing datasets (e.g., global climate projections).

The current project builds off existing observation-based and modeling studies within and beyond the Rio Grande Basin by implementing a version of the Weather, Research, and Forecasting (WRF) model coupled to a 1-D lake model (WRF-Lake) to simulate lake evaporation and the physical processes that drive this variable at Elephant Butte Reservoir. The WRF model has been used by researchers and practitioners across the world to simulate regional climate and physical processes at scales relevant to decision makers (e.g., Reclamation 2019, Reclamation 2020). Thus, the objectives of the current project are 1) to use the WRF model coupled to the 1-D lake model, WRF-Lake, to estimate daily, monthly, and annual evaporation losses from across Elephant Butte Reservoir, 2) to compare simulated total evaporation estimates from the WRF model with alternative estimates, and 3) to submit this study for publication in a scientific journal. We accomplish these objectives using output from a coupled WRF/WRF-Lake simulation performed using high-performance computing resources provided by the Department of Interior's (DOI's) High-Performance Computing (HPC) center hosted by the United States Geological Survey (USGS).

2 Study Details

2.1 Methods

The WRF modeling system is a community-based modeling system that was originally developed to serve the atmospheric research and numerical weather prediction communities. The WRF model is designed to solve the governing equations (e.g., conservation of mass, conservation of momentum, conservation of energy) based on initial conditions and transient conditions provided at domain boundaries. The flexible model architecture allows for a variety of designs and setups tailored to each user's needs. The model is fully compressible (i.e., the density of air can vary) and can be run under nonhydrostatic conditions (i.e., the vertical pressure gradient does not have to equal buoyancy forces). Models that assume hydrostatic balance (i.e., are based on the hydrostatic primitive equations) are unable to accurately represent the dynamics of many small-scale processes, such as flows over hills and mountains and the dynamics of deep convective storms (Clark et al. 2006).

In this study, we utilize version 4.2.0 of the WRF modeling system coupled to WRF-Lake to simulate evaporation across EBR. The full modeling domain, with one outer domain (d01) and two inner domains (d02, d03), is shown graphically in Figure 2.1. A summary of domain details is provided in Table 2.1. EBR is located within d03, the domain with the finest horizontal resolution and time step. The full simulation runs from January 1, 1994, 00 UTC, to February 1, 1996, 00 UTC. However, we exclude the first full month of simulation to give the coupled system time to spin-up. Spin-up time is generally thought of as the amount of time required for a give modeling system to stabilize after initiation. Each model configuration and setup can have differing spin-up needs. We allow for a full month of spin-up based on results from Gu et al. (2015), who simulated conditions in the Great Lakes basin with a coupled version of WRF.

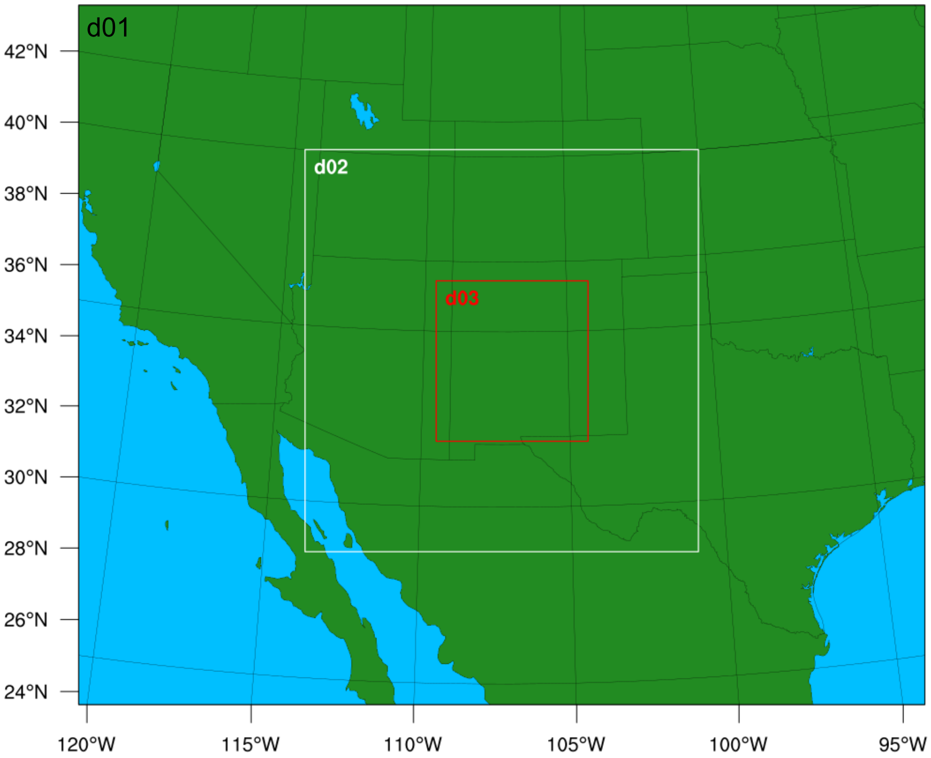

Figure 2.1 – WRF modeling domain. Horizontal resolution increases from 9 km in d01 to 3 km in d02 to 1 km in d03.

Table 2.1 – Supporting details of WRF domains.

Domain	Horizontal Resolution (km)	Time Step (sec)	Number of Grid Cells (x×y)	Number of Vertical Layers	Forced By
d01	9	30	300×248	54	CFSR
d02	3	10	418×427	54	d01
d03	1	3	484×511	54	d02

We implement the parameterization schemes of Vivoni et al. (2009) in WRF and force the outermost domain with historical reanalysis data from the Climate Forecast System Reanalysis (CFSR) dataset (Saha et al. 2010). This reanalysis dataset provides initial conditions and six-hourly boundary conditions at a 30 km horizontal resolution and 38 vertical levels across the globe. Following guidance from WRF-Help and Gómez and Miguez-Macho (2017), we activate spectral nudging above the planetary boundary layer in the outermost domain, d01. Spectral nudging is a technique used in numerical weather prediction modeling to prevent large and unrealistic departures between the forcing datasets (often global scale) and the simulated data (regional scale). Numerical solutions within the regional model (in this case, WRF) are relaxed towards the forcing dataset (CFSR).

One of the many benefits of using a regional numerical weather prediction model to simulate climate is the ability to capture small-scale variations in topography. Figure 2.2 shows simulated terrain height (m) within the innermost WRF domain (d03). Terrain heights within this domain range from 979 m to 3720 m above sea level. Water bodies are represented by black shading. EBR is located between 33°N and 34°N.

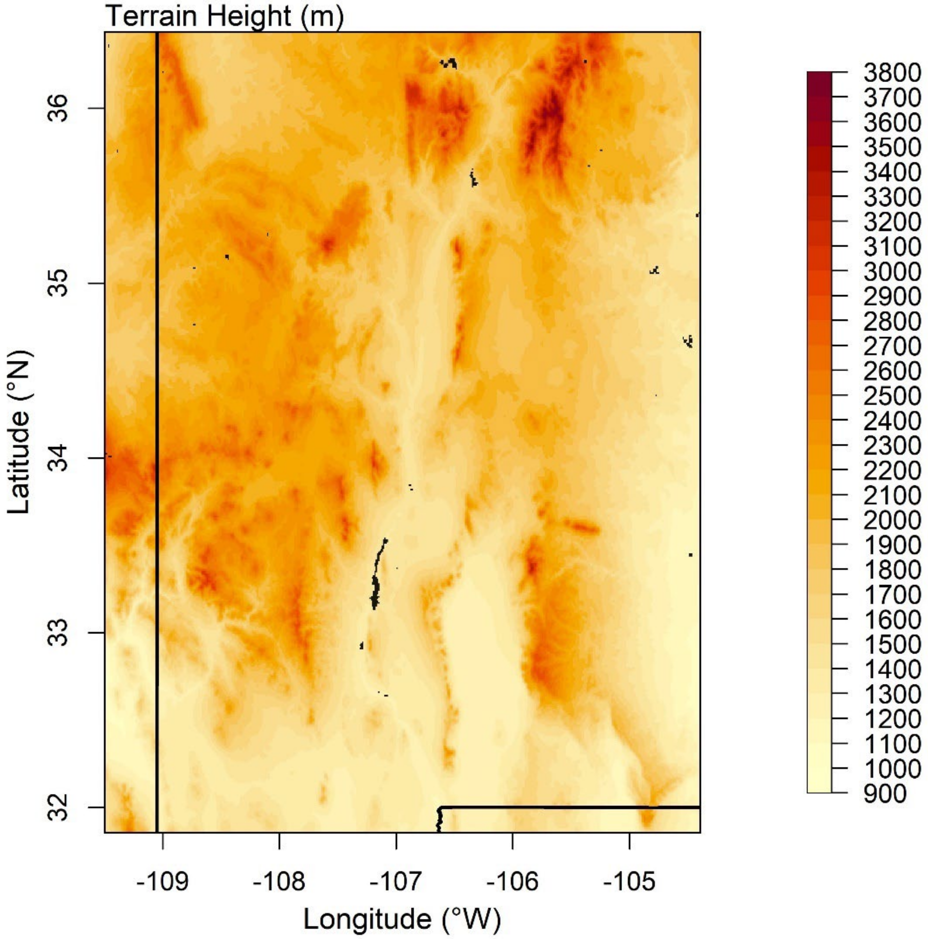

Figure 2.2 – Terrain height (m) within the innermost WRF domain.

We simulate EBR using a version of the default lake model included in the WRF modeling system, WRF-Lake (Gu et al. 2015). The lake model is a 1-D energy budget scheme that allows for up to five ice layers, 10 water layers, and 10 soil layers. We modify the default lake mask in WRF-Lake using the spatial extent of the reservoir recorded during a 1999 survey trip (Reclamation 1999). The left plot of Figure 2.3 shows the lake mask used to simulate a reservoir within WRF-Lake. We determine depth of the water column (right plot of Figure 2.3) using reservoir bathymetry data recorded during the same survey trip. We assume a constant reservoir water surface elevation between February 1, 1994, and January 31, 1996, (4405.226 ft) and subtract reservoir bottom terrain from the 1999 survey to yield water column depth.

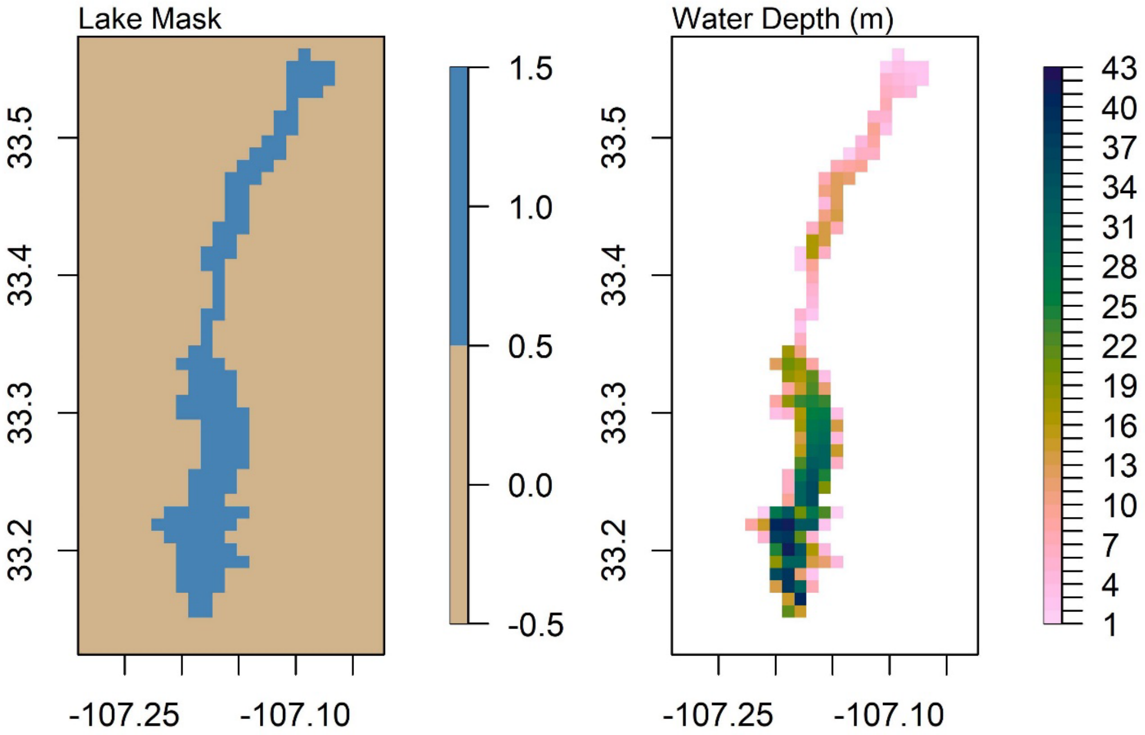

Figure 2.3 – Lake mask and water column depth (m) as simulated by the coupled WRF/WRF-Lake method at Elephant Butte Reservoir. Blue values in the left plot represent locations where the lake model is turned on.

Evaporation, also referred to as latent heat flux, in WRF-Lake is estimated using a version of the bulk-aerodynamic equation. See Oleson et al. (2004; 2010) for details on this method. The default units of evaporation in the model are W m^{-2}, which we ultimately convert to mm $month^{-1}$. These units can be presented as rates (i.e., depth per time) or as totals valid over some specified amount of time. We use this language interchangeably within the report, as all totals over some amount of time can be expressed as a depth over the same time (i.e., rate).

We compare simulated evaporation estimates from WRF-Lake with three alternative datasets. The first dataset represents evaporation totals measured at a Class A pan located on the southern side of the reservoir. The second dataset is based on evaporation estimates developed using the Complementary Relationship Lake Evaporation (CRLE; Morton 1979; Huntington et al. 2015) model. Specifically, we force CRLE with output from the WRF model averaged over a 3 km buffer surrounding the reservoir. The final dataset that we use for comparisons is the Global Lake Evaporation (GLEV) dataset by Zhao et al. (2022). Additional details on each of these datasets is available in Appendix A (Holman et al.,2022).

2.2 Results

The coupled WRF/WRF-Lake method outputs dozens of variables at an hourly temporal resolution with a spatial resolution tied to the domain from which the variable originates. While this high-frequency data can be useful for answering scientific questions, we focus this section on monthly and annual evaporation totals to remain succinct. For details on other variables from the coupled system, contact the author of this report.

Figure 2.4 shows monthly evaporation totals for grid cells across EBR between February 1994 and January 1996 as simulated by the coupled WRF/WRF-Lake method. Values in the upper left of each subplot represent the monthly average (mm) estimated evaporation rate, while values in the lower right of each subplot represent the monthly range of accumulated totals (mm) across the reservoir surface. At the monthly timescale, we see that there is a general increase in reservoir-average evaporation from February to July 1994, with a decline in reservoir-average evaporation from July to December 1994. We see an increase in reservoir-average evaporation from December 1994 to January 1995, followed by a decrease between January and February 1995. Reservoir-average evaporation increases from February to September 1995 and declines again from September to December 1996. The range of evaporation totals across the reservoir surface tends to be lowest during cool-season months, particularly late winter (e.g., January 1995 and February 1995). These periods of homogeneous surface evaporation likely occur after vertical mixing has occurred throughout the reservoir. Alternatively, the range of evaporation totals across the reservoir surface appears to be greatest during the early and/or late warm season (e.g., June 1994, September 1994, May 1995), when the water column is heating and/or cooling. These findings demonstrate the existence of spatial homogeneity in reservoir evaporation during cool season months and spatial heterogeneity in reservoir evaporation during transition months.

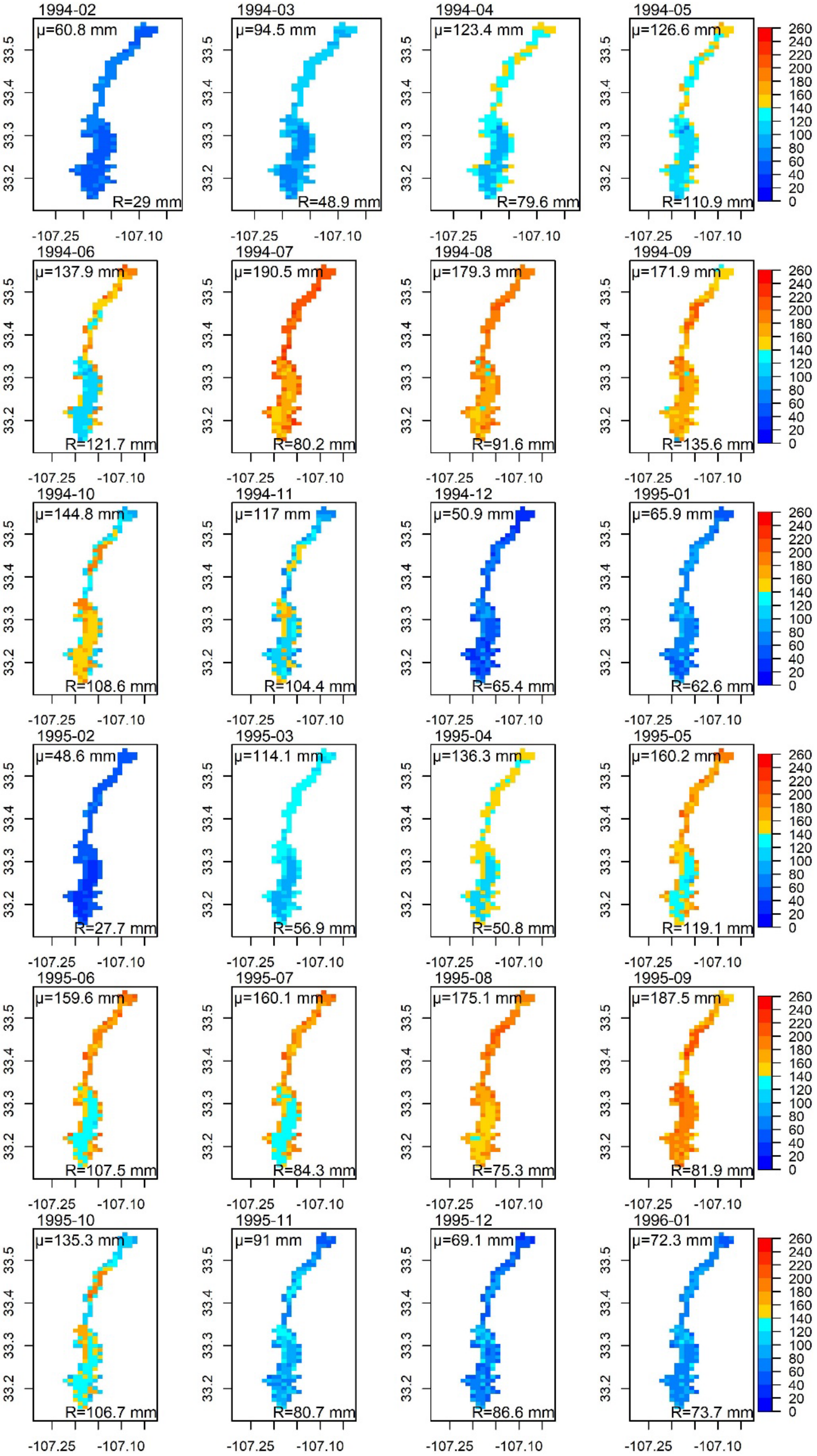

Figure 2.4 – Total monthly evaporation losses (mm) across Elephant Butte Reservoir between February 1994 and January 1996 (top left to bottom right). Figure modified from Holman et al. (2022).

Annual evaporation totals across EBR during the study period are shown graphically in Figure 2.5, along with the reservoir average value and range of totals. Results in both plots suggest that during this period of simulation, annual losses are lowest in the southern portion of the reservoir, where water depth is greatest. Annual losses are greatest north of the "narrows", the narrow section of the reservoir located near 33.4°N latitude, where water depths are between 13 to 18 m (see right plot of Figure 2.3). Reservoir-average evaporation is less during the first year of the simulation than the second year of the simulation, a difference of approximately 45 mm. Similarly, the range of annual totals is smaller during the first year (482 mm) compared to the second year (545 mm).

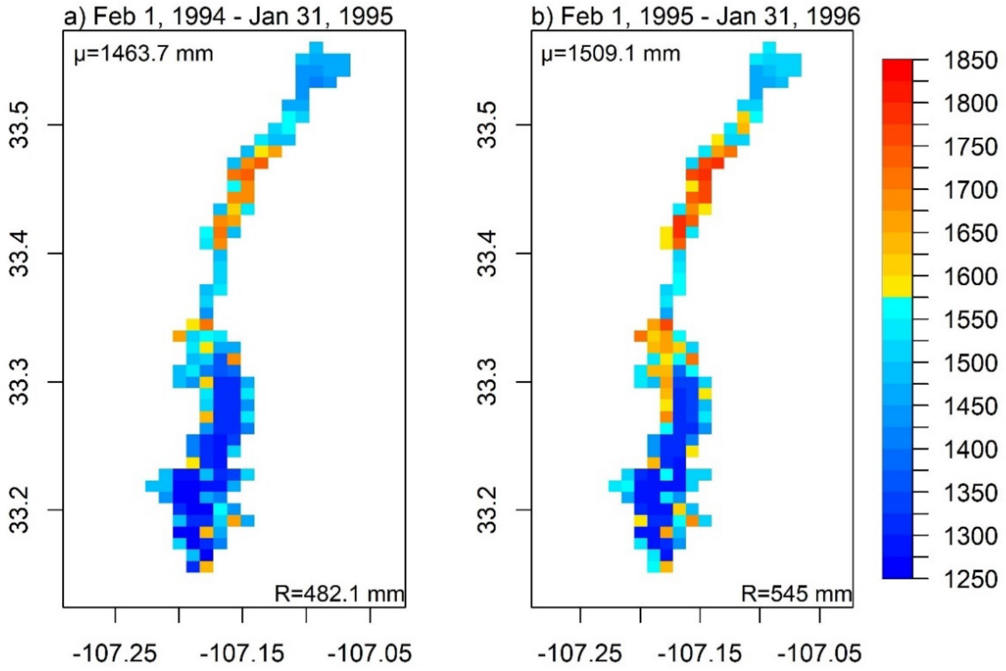

Figure 2.5 – Total annual evaporation (mm) across Elephant Butte Reservoir between (left) February 1, 1994, and January 31, 1995, and (right) February 1, 1995, and January 31, 1996. Figure from Holman et al. (2022).

Monthly and annual reservoir-average evaporation estimates from WRF-Lake and three other datasets are shown in Figure 2.6. Results in the top plot show how reservoir-average evaporation varies during the two-year study period. We see that Class A pan evaporation totals peak during June of both years, near 215 to 220 mm, which is earlier than all other methods. The earlier timing of peak evaporation in Class A pan records is generally considered a result of a lack of heat storage within the pans. Unlike the Class A pan evaporation totals in Figure 2.6, monthly total evaporation estimates from the CRLE method peak two months later, in August of both years, with magnitudes near 250 mm/month. Results from the GLEV dataset show a monthly peak during July of the first year (near 180 mm/month) and October during the second year (near 180 mm/month). This is similar to results from the coupled WRF system, which peaks during July the first year (near 195 mm/month) and September the second year (near 190 mm/month). Results from the WRF system agree best with the GLEV dataset, both in terms of the monthly progression and peak monthly totals.

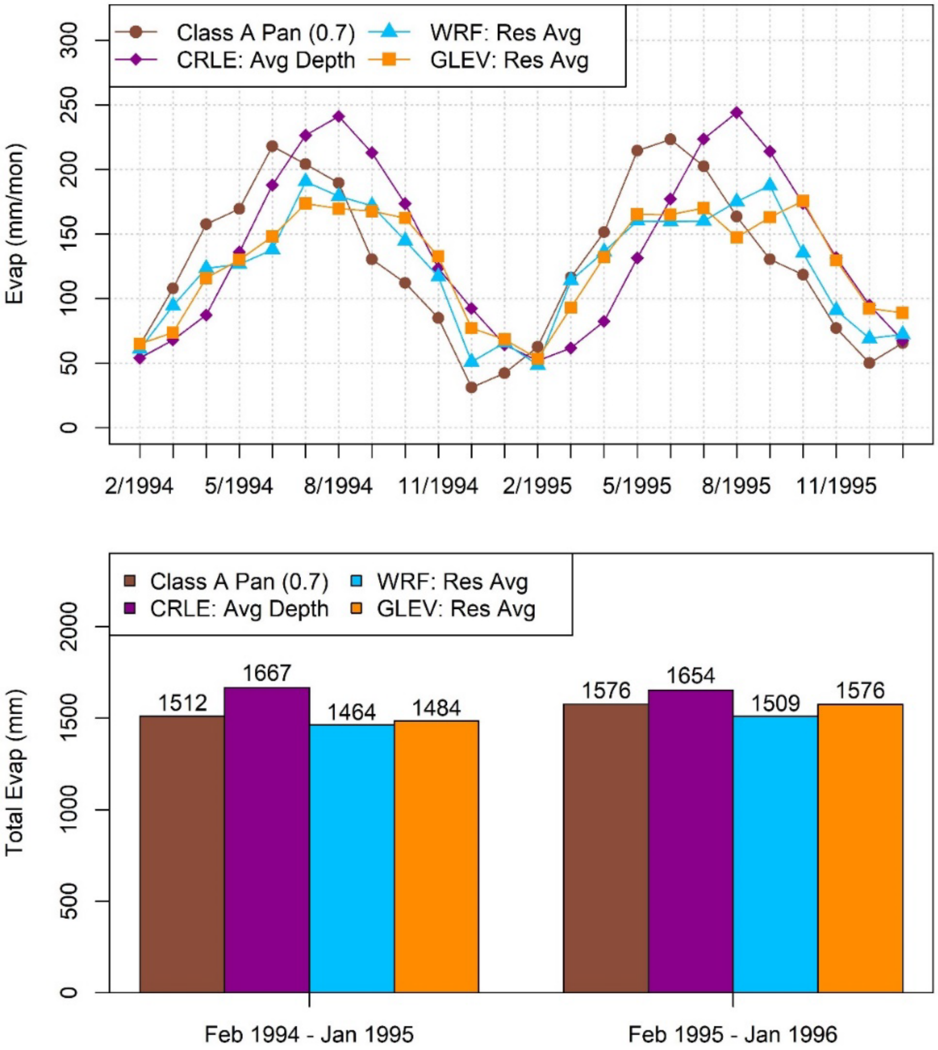

Figure 2.6 – Monthly evaporation from Elephant Butte Reservoir based on Class A pan estimates, the CRLE model, WRF coupled to WRF-Lake, and GLEV. Figure from Holman et al. (2022).

Annual totals among the five datasets are shown in the bottom plot of Figure 2.6. These totals reflect two separate 12-month periods of the full simulation. Results indicate that annual totals from the CRLE model exceed all other methods during both years. Results also show that CRLE totals during the second year are less than during the first year, a result that is opposite of all other methods. Annual totals among the three other methods (Class A pan, WRF-Lake, and GLEV) range from 1464 mm and 1512 mm during the first year and 1509 mm and 1576 mm during the second year. The two plots in Figure 2.6 suggest that annual totals can show agreement among methods at the expense of the monthly distribution (i.e., compensating differences throughout the seasonal cycle).

In general, monthly total volumetric evaporative losses are of greater interest to water managers than evaporation rates, as volumetric losses help support water accounting computations. We compute monthly and annual volumetric evaporative losses during the study period using the spatially heterogeneous evaporation rates across EBR as simulated by the coupled WRF/WRF-Lake method. Monthly volumes (acre-ft) from WRF-Lake are shown in Figure 2.7 along with estimates from the GLEV dataset. Results show general agreement between the two datasets, although volumes from WRF-Lake are typically greater than those from GLEV. There are a few exceptions to this finding, which occur during December 1994 and between November 1995 and January 1996, when GLEV volumetric losses exceed those from WRF-Lake. During the first simulation year, both datasets show peak volumetric losses during July 1994. Conversely, during the second simulated year, volumetric losses from WRF-Lake peak during September 1995, while peak volumetric losses from the GLEV dataset occur during October 1995. These cool-season differences during the second year align with differences in evaporation rates noted between the two datasets (e.g., see top plot of Figure 2.6). Annual volumetric evaporative losses from the two methods are summarized in Table 2.2. We see that volumetric evaporative losses from WRF-Lake exceed those from GLEV by 22000 and 17600 acre-ft during the first and second years, respectively. These differences are likely related to subtle differences in evaporation rates that, when combined with differences in reservoir surface area, produce different volumetric losses. Note that WRF-Lake uses a fixed reservoir surface area, while GLEV allows for surface area to vary.

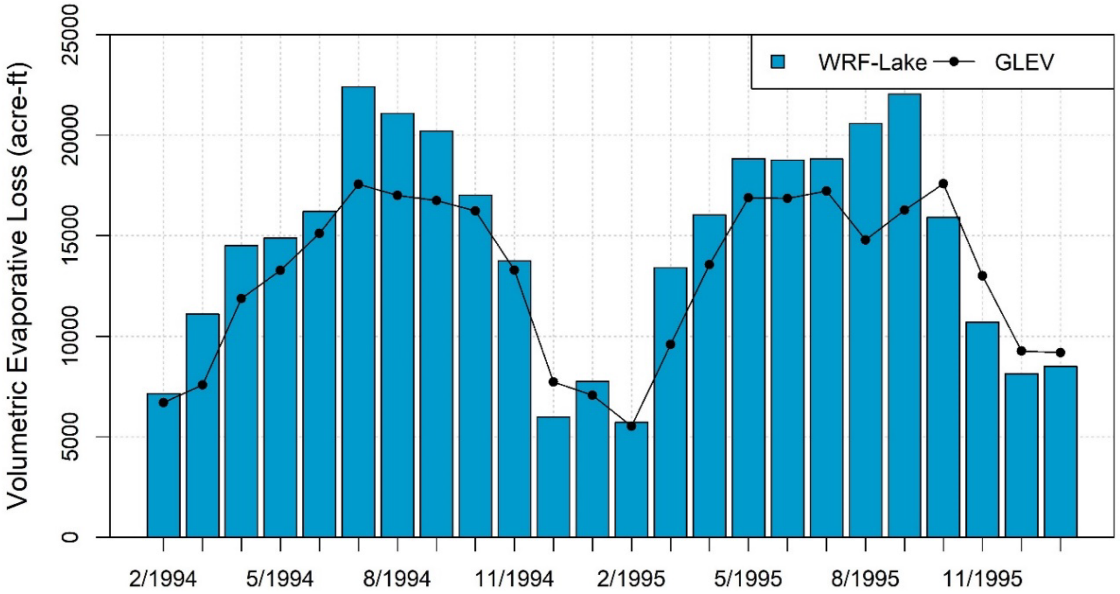

Figure 2.7 – Monthly volumetric evaporative losses (acre-ft) at Elephant Butte Reservoir based on the coupled WRF/WRF-Lake method and the GLEV dataset during the simulation period.

Table 2.2 – Total volumetric evaporative losses at Elephant Butte Reservoir based on results from the coupled WRF/WRF-Lake method and GLEV dataset.

Time Period	Total Volumetric Losses (acre-ft)	
	WRF/WRF-Lake	GLEV
Feb. 1994-Jan. 1995	172060.7	150188.8
Feb. 1995-Jan. 1996	177396.9	159731.7

2.3 Dissemination

Project information has been disseminated within and beyond Reclamation via a number of different mechanisms. For example, team members presented on the topic at a reservoir evaporation workshop meeting held on November 11, 2020, hosted by Reclamation's Research and Development Office. Team members also presented project details at multiple Water Resources Engineering and Management group meetings within the TSC. These meetings led to ideas for WRF-Lake model calibration efforts and additional discussion points on the study. Team members presented on the project at multiple monthly meetings with the Albuquerque Area Office (AAO) and partners within the AAO service area. These conversations provided context on regional hydroclimate conditions, availability of historical observations, and region-specific concerns. Team members were also asked to present project details at two Rio Grande Compact Engineer Advisor's meetings, one in 2021 and again in 2022.

Beyond presentations, team members are preparing a scientific manuscript for publication in the *Journal of Hydrometeorology*. Finally, team members have uploaded project data, specifically, reservoir-average evaporation rates at an hourly time step between February 1, 1994, 00:00 UTC and January 31, 1996, 23:00 UTC, to the Reclamation Information Sharing Environment (RISE). Technical tools used to support the data upload will be shared with study partners from the AAO and members of the TSC.

3 Project Benefits

3.1 Partner Involvement

This project was executed with regular involvement among Reclamation employees in the Technical Service Center (TSC) and AAO and study partners from other institutions. Specifically, the AAO Planning Group organized monthly calls among partners broadly focused on evaporation in the Rio Grande Basin. Through these calls, information and data were shared within and across Reclamation and its research partners, and this exchange provided some needed resources and data for this project. Shared variables included historical water temperature observations, depth-area curves, and Secchi depth observations of water clarity, which were used to support WRF-Lake modeling efforts.

Coordinated monthly meetings also involved discussions among researchers from different organizations. For example, Dr. Salim Bawazir regularly attended the monthly evaporation meetings. Dr. Bawazir shared with report authors previous documents, reports, and draft EC evaporation estimates from a currently deployed EC station at EBR. Dr. Bawazir also provided photos of weather stations around the reservoir. Dr. Bawazir acted as a regional expert on evaporation from EBR with a tendency to share easily. Monthly meetings also involved useful conversations with Dr. Jake Collison. Dr. Collison is operating a Collison Floating Evaporation Pan on multiple Reclamation reservoirs, including EBR. Dr. Collison was happy to share data and information where relevant to our overall project goals.

Eventually, monthly calls with the AAO grew to include researchers and practitioners from the Texas Water Development Board and Texas A&M University. These monthly calls always focused on evaporation projects underway across agencies and led to useful discussion. Authors of the current report learned of the GLEV dataset that was used in this study (see section 2.1) through these discussions among agencies.

3.2 Management and Operations

Project benefits related to management and operations include:

1) development of a method to calculate total monthly and annual volumetric reservoir evaporation losses, key components of the water budget that are critical to water management.
2) demonstration of the potential evaporative water losses associated with increasing water levels in EBR such that the reservoir extends north of the "narrows" where higher evaporation totals were simulated.
3) improvements to understanding of evaporative losses across Elephant Butte and their importance within the broader context of the Middle Rio Grande and Rio Grande Projects.
4) development of an additional evaporation dataset that can be used to understand limitations of existing reservoir evaporation estimates (e.g., Class A pan) used in Rio Grande Basin hydrologic modeling efforts, particularly at sub-seasonal time scales.
5) highlighted potential limitations of extrapolating point, in-situ observations across the surface of EBR.

3.3 Technical Capacity

The technical capacity of Reclamation employees has benefited from this project in multiple ways. These benefits including proficiency with the use of a supercomputing resource, new WRF modeling tools, and exploration of new/alternative evaporation rate datasets.

Members of the TSC performed all WRF simulations on the DOI's HPC supercomputing system, hosted by the USGS. This is the first example of TSC employees using an HPC system in support of water management within one of Reclamation's water projects, and therefore significantly developed in-house capabilities with this super computing system. Through this project, members of the TSC gained access to the HPC system, attended training by USGS employees, and established useful workflows to support future studies using this amazing resource.

Although team members have employed numerical weather prediction models in the past; this project is the first instance in which Reclamation staff coupled a numerical weather prediction model to a lake model to better understand dynamics at one of Reclamation's reservoirs. To make this possible, team members had to modify several variables within the coupled WRF system including the lake/land mask, reservoir bathymetry, and initial water surface temperatures. This progress will ease future applications of the coupled WRF/WRF-Lake system.

This project also allowed Reclamation staff to increase familiarity with several evaporation datasets. Specifically, funding from this project allowed members of the TSC to gain proficiency with a new lake model, the CRLE model. An informal training session was held within the Water Resources Engineering and Management group in January 2022. Similarly, team members were able to learn about and use a new reservoir evaporation dataset, GLEV. The GLEV dataset and improvements to it are currently being funded by NASA. Reclamation is a partner on that project, along with Texas A&M University, the Desert Research Institute, and Virginia Tech University. The existing dataset, and any later versions, will likely be used for comparisons in many future reservoir evaporation studies at Reclamation.

3.4 Lessons Learned

In this study, we learned that the use of a numerical weather prediction model, WRF, coupled with a 1-D lake model (WRF-Lake) is capable of developing estimates of evaporation loss rates across a reservoir that are comparable with other available methods. We also learned that this method can simulate spatial variations in loss rates across a reservoir, and therefore can provide estimates of total volumetric loss rates from the reservoir on a monthly and annual basis, key parameters sought by water managers. The method tested in this study therefore provides an advantage over point-measurement methods. However, this important information comes at a high computational cost and requires access to a super-computer. Also, the results are highly dependent on the quality and availability of local measurements and observations, which may or may not be available at a given Reclamation reservoir. Therefore, the applicability of this method in Reclamation is limited to reservoirs for which the necessary data are available and of sufficient quality. The performance of this method is further limited to practitioners with access to a supercomputer to support the model simulations.

Team members would not have been able to perform the computationally expensive coupled simulations performed in this study with existing hardware in the Water Resources Engineering and Management group of the TSC. We were able to benefit from free access to the DOI’s HPC system hosted by USGS, which is an amazing supercomputing resource. At EBR, the WRF-Lake calibration efforts were restricted by a lack of observational data. In future applications of the WRF/WRF-Lake method, team members will look for alternative historical observational datasets to support calibration efforts.

4 Conclusions

4.1 Summary

In this study, we implemented the WRF model coupled to a 1-D energy-balance lake model, WRF-Lake, to simulate historical hydrometeorological conditions at EBR, a reservoir on the Rio Grande in south-central New Mexico that is vital to water deliveries among US states and to Mexico and is currently the focus of multiple other research efforts focused on improving estimation of reservoir evaporation. Through our modeling efforts, we developed spatial estimates of evaporation across the reservoir surface between February 1994 through January 1996, along with estimates of monthly and annual total evaporative loss volumes from the reservoir during the same period. We chose to focus on this historical period because water levels in the reservoir were relatively stable, surface area was at record high levels, and evaporation volumes were correspondingly large (as high as 177,000 acre-ft per year).

In order to better understand evaporation estimates from the WRF model, we compared simulated reservoir averaged total evaporative losses over the study period with three alternative datasets valid over the same historical time period. Those datasets include Class A pan records (with a pan coefficient of 0.7), output from the Complementary Relationship Lake Evaporation (CRLE) model forced with meteorological conditions from the WRF model, and output from the Global Lake Evaporation Volume (GLEV) dataset. CRLE and GLEV estimates are available at monthly timesteps and represent average conditions over the reservoir. Conversely, coupled WRF/WRF-Lake output is available at an hourly temporal resolution and 1 km spatial resolution. Comparisons among the four different methods showed that monthly Class A pan evaporation totals peaked earlier than the other three methods during both years, consistent with previous research noting the lack of heat storage in the pans. Results also showed that monthly peak evaporation totals from the Class A pan and CRLE methods exceeded WRF-Lake and GLEV estimates during both years. Finally, results showed that coupled estimates from the WRF method agreed best with estimates from the GLEV dataset.

We took the analysis of simulated evaporation rates from the coupled WRF/WRF-Lake method one step further by computing monthly volumetric evaporative losses. We compared these volumes to estimates from the GLEV dataset. Results showed that monthly volumetric evaporative losses from WRF-Lake typically exceeded those from GLEV with some exceptions during cool-season months. When aggregated to an annual scale, WRF-Lake volumetric evaporative losses were up to 22000 acre-ft higher than GLEV estimates. Annual volumetric evaporative losses from both methods presented in this study are less than previous estimates cited in the 2004 Middle Rio Grande Water Supply Study (S.S. Papadopoulos & Associates, 2004).

4.2 Future Application

There are numerous potential applications of the coupled WRF/WRF-Lake method to water resources planning and management questions at Reclamation and beyond. However, we suggest four primary areas of continued application:

a) understanding spatial and temporal variability in evaporation during other historical time periods and at other reservoirs.
b) validating alternative evaporation estimates with a method that incorporates a) two-way coupling between lake and atmosphere and b) heat storage within the water column.
c) developing future projections of reservoir evaporation using a coupled modeling system, where heat storage is retained from one year to the next (i.e., memory within the lake itself).
d) developing over-lake estimates of other hydrometeorological variables, such as, but not limited to, precipitation, wind speed, and atmospheric moisture.

4.3 Data Availability

Daily reservoir-average evaporation estimates from the coupled WRF/WRF-Lake method are being uploaded to the Reclamation's Information Sharing Enterprise (RISE). The data can be obtained at https://data.usbr.gov.

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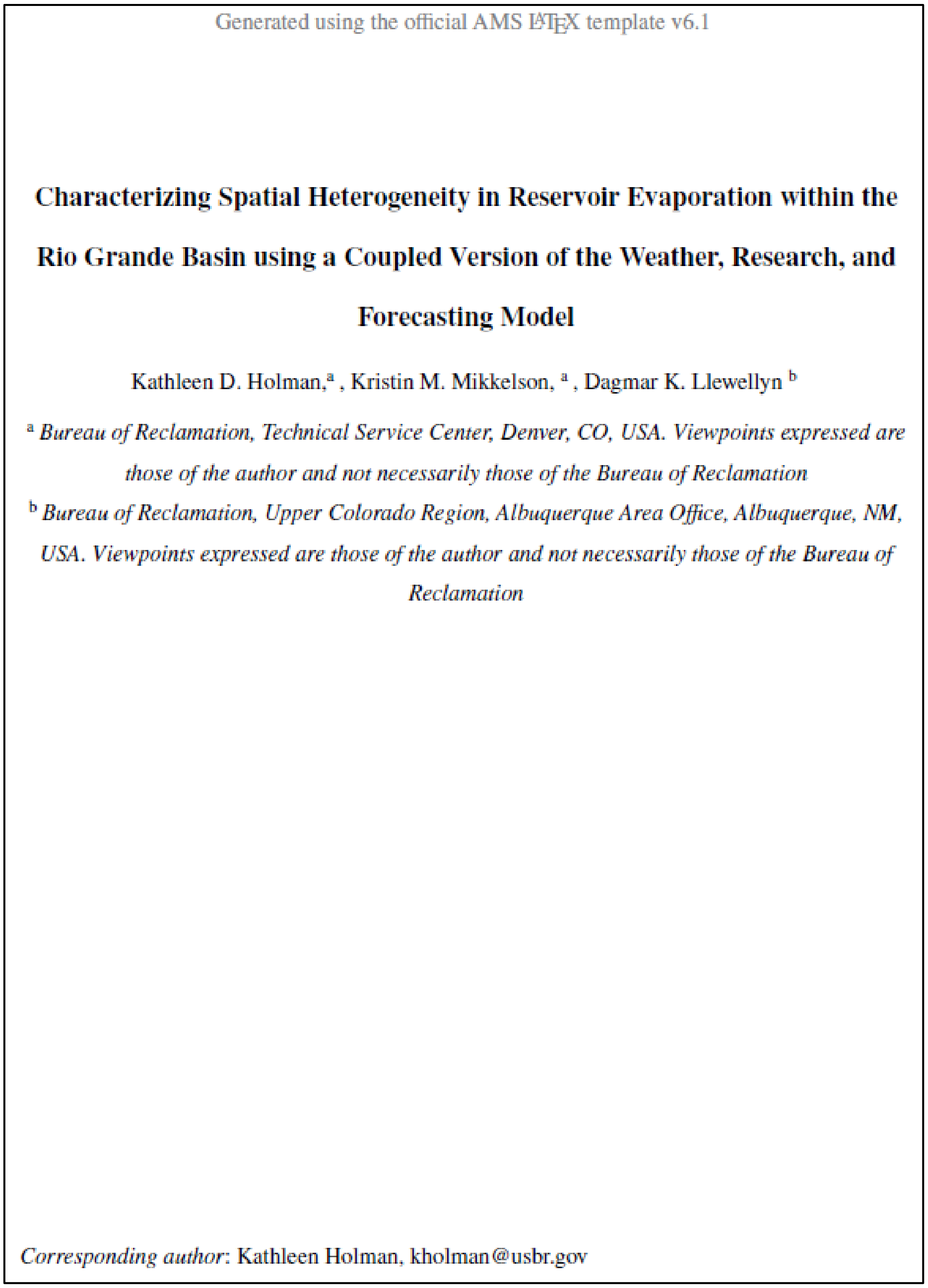
6 Unit Conversions

Metric	**Imperial**
25.4 mm	1 inch
°C	°F=(°C*(9/5))+32
0.3048 m	1 ft
1 km^3	810714 acre-feet

Appendix 1. Manuscript in Preparation



Characterizing Spatial Heterogeneity in Reservoir Evaporation within the Rio Grande Basin using a Coupled Version of the Weather, Research, and Forecasting Model

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