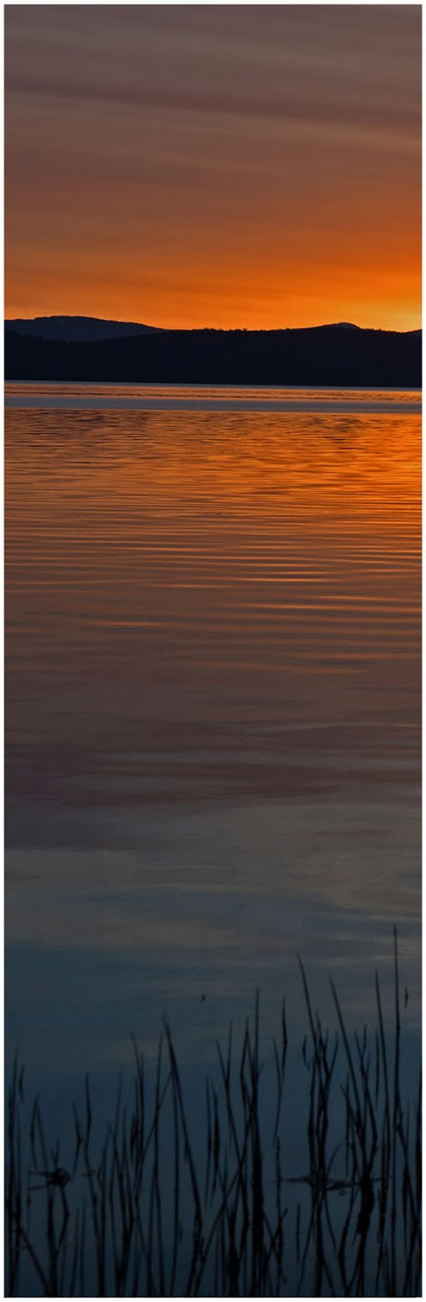
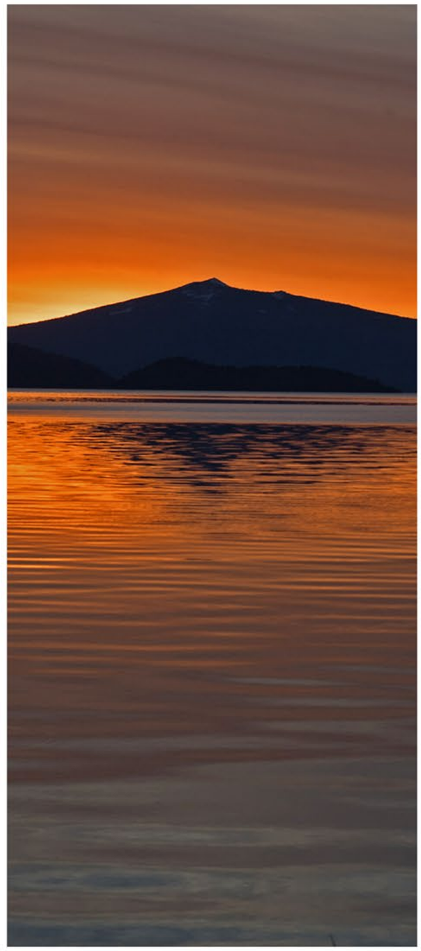
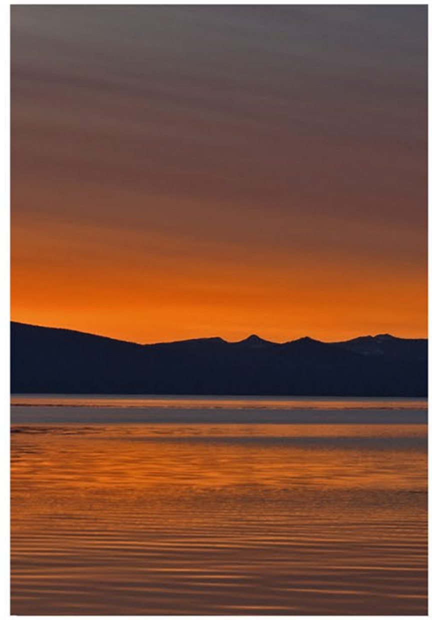

# Klamath River Basin Revised Natural Flow Study

# Phase 1 & 2 Open Water Evaporation Modeling

Technical Memorandum ENV-2024-006

BUREAU OF RECLAMATION

November 2023

# Mission Statements

The U.S. Department of the Interior protects and manages the Nation's natural resources and cultural heritage; provides scientific and other information about those resources; honors its trust responsibilities or special commitments to American Indians, Alaska Natives, and affiliated Island Communities.

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

Technical Memorandum ENV-2024-006

# Klamath River Basin Revised Natural Flow Study Phase 1 & 2 Open Water Evaporation Modeling

**Klamath Project**
**California Great Basin Region**



Prepared by:

**Bureau of Reclamation**
**Technical Service Center**
**Denver, Colorado**

**U.S. Department of the Interior** **October 2023**

**Technical Memorandum ENV-2024-006**

# Klamath River Basin Revised Natural Flow Study Phase 1 & 2 Open Water Evaporation Modeling

## Klamath Project
## California Great Basin Region



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# Acronyms and Abbreviations

| | |
|---|---|
| 1-D | One-dimensional |
| ac | acre |
| ACAP | area-capacity |
| CRLE | Complementary Relationship Lake Evaporation |
| DLEM | Daily Lake Evaporation Model |
| EC | eddy covariance |
| ET | evapotranspiration |
| ETO | grass reference ET |
| ft | feet |
| ft amsl | feet above mean sea level |
| GLDAS | Global Land Data Assimilation System |
| GLEV | Global Lake Evaporation Volume |
| gridMET | Gridded Surface Meteorological dataset |
| GSWD | global surface water dataset |
| in | inch(s) |
| in/day | inches per day |
| KBAO | Klamath Basin Area Office |
| Klamath Project | Reclamation's Klamath Basin Irrigation Project |
| km | kilometer |
| $km^2$ | square kilometers |
| LEM | Lake Evaporation Model |
| LKB | Lower Klamath Basin |
| LKL | Lower Klamath Lake |
| $mi^2$ | square miles |
| NAIP | National Agriculture Imagery Program |
| NAVD88 | North American Vertical Datum of 1988 |

| | |
|---|---|
| NFS | Natural Flow Study |
| NGVD29 | National Geodetic Vertical Datum of 1929 |
| NHDPLUS HR | National Hydrography Plus High Resolution |
| NWR | National Wildlife Refuge |
| PacifiCorp | Pacific Power Corporation |
| Reclamation | Bureau of Reclamation |
| RTMA | Real-Time Mesoscale Analysis |
| TAF | thousand acre-feet |
| TIN | triangular irregular network |
| TM | Technical Memorandum |
| TSC | Technical Service Center |
| UKB | Upper Klamath Basin |
| UKL | Upper Klamath Lake |
| USGS | United States Geological Survey |
| $W/m^2$ | Watts per square meter |
| WY | water year |

## Symbols

| | |
|---|---|
| °F | degrees Fahrenheit |
| = | equals |
| < | less than |
| ± | plus or minus |

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## Appendices

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A Supporting Figures and Tables – Open Water Evaporation Modeling

# I. Introduction

## A. Background

In 2005, the Bureau of Reclamation (Reclamation) completed a Natural Flow Study (NFS) of the Upper Klamath River Basin above Keno, Oregon (Reclamation 2005). The purpose of that study was to provide monthly natural streamflow estimates of the Klamath River at Keno, Oregon, where natural streamflow was defined as 'typical flow without agricultural development in the Upper Klamath River Basin, including its tributaries'. Following this NFS, the National Research Council (NRC) provided comments and suggestions for improving upon these natural flow estimates (National Research Council 2008). These suggestions ranged from increasing the timestep from monthly to daily, to including changes in land use from activities such as forest fire suppression and logging. In response to the NRC report, Reclamation's Technical Service Center (TSC) was tasked with estimating refined natural streamflow estimates throughout the Klamath River Basin in a comprehensive NFS. For this study, natural streamflow is defined as the streamflow that would have occurred in the absence of land use changes (e.g., agriculture, forestry, etc.), major development (e.g., roads, railroads, municipalities, etc.), and water management (e.g., dams, hydroelectric plants, etc.). The overarching goal of this study is to advance science in the Klamath Basin, and thereby support future analyses and studies throughout the basin. Primarily, this study leverages current science, methods, and tools to develop revised natural streamflow estimates for the Klamath River Basin, while improving upon limitations of previous estimates (Reclamation 2005) and incorporating comments provided by the NRC (National Research Council, 2008). The resulting natural streamflow estimates may be of use in habitat studies, drought planning, water supply decision making, and other water resource studies.

## B. The Klamath Basin

The Klamath River flows east to west from its headwaters near Crater Lake in southern Oregon to its outflow at the Pacific Ocean in northern California (figure 1). The Klamath River Basin has a diverse environment, spanning multiple distinct climate zones and ecological habitats, and is typically divided into two portions: Upper and Lower Klamath Basins. The Upper Klamath Basin (UKB) drains all catchments above Iron Gate Dam, California. Located in the rain shadow on the eastern side of the Cascade Mountain Range, this portion of the basin has an arid climate. Vegetation within the UKB is primarily drought-tolerant trees, such as lodgepole and ponderosa pines, along with shrubs, grasslands, and even wetlands in the lower elevations and near lakes. However, despite its aridity, the UKB features Oregon's largest natural lake by surface area—Upper Klamath Lake (UKL)—and extensive urban and agricultural development. In contrast, the Lower Klamath Basin (LKB), which is located in the Pacific Coastal Range, receives ample precipitation. The LKB is well forested by a palette of northern California and Pacific Northwest conifers and hardwoods. The LKB has no major natural lakes and less urban and agricultural development than in the UKB.

Indigenous people have inhabited the Klamath River Basin since time immemorial (Beckham 2006). Presently, the basin is home to six federally recognized Indian Tribes: the Yurok Tribe; Hoopa Valley Tribe; Karuk Tribe; the Klamath Tribes, comprised of Klamath, Modoc, and Yashooskin; Quartz Valley Indian Community; and Resighini Rancheria (77 FR 47868). Numerous native groups not federally recognized, such as the Shasta people, inhabit parts of northern California and southern Oregon. Although they are not federally recognized, some of them have been inducted into the Karuk Tribe (Beckham 2006). The Klamath River and canyon are considered sacred by the native tribes (Bureau of Land Management 1990). Management practices of the native people left much of the natural landscape unchanged prior to non-native settlement.

Early non-native settlers began entering the region in the early 1800s. Early settlers focused on agricultural production including farming and ranching. The abundance of large, flat, grassy meadows with plenty of lakes and marshy areas to provide water encouraged the expansion of grazing in the UKB (Stene 1994). In 1905, Congress authorized Reclamation to begin the Klamath Project, a project designed to locate and construct irrigation networks designed to support productive agricultural communities. The Klamath Project was unique to other federal-sponsored projects in the arid west due to the nature of the landscape. Rather than transform arid lands into farmlands, Reclamation sought to drain the wetlands located around the natural lakes—UKL, Lower Klamath Lake (LKL), and Tule Lake—and transform them into reclaimed agricultural lands. To accomplish this vision, over the next 20 years Reclamation constructed a labyrinth of canals, dams, and drainage canals to facilitate the transition of the UKB into a productive agricultural community. In addition to the Klamath Project, and with the arrival of the railroad in 1909, timber harvesting activities grew in the basin.

By 2022, the Klamath River Basin was much altered from its natural state, with land use, development, and water management practices directly impacting the UKB, and affecting the flow regime and ecology of the LKB. The current streamflow regime is fundamentally different than the natural streamflow that would exist without these changes to the basin.

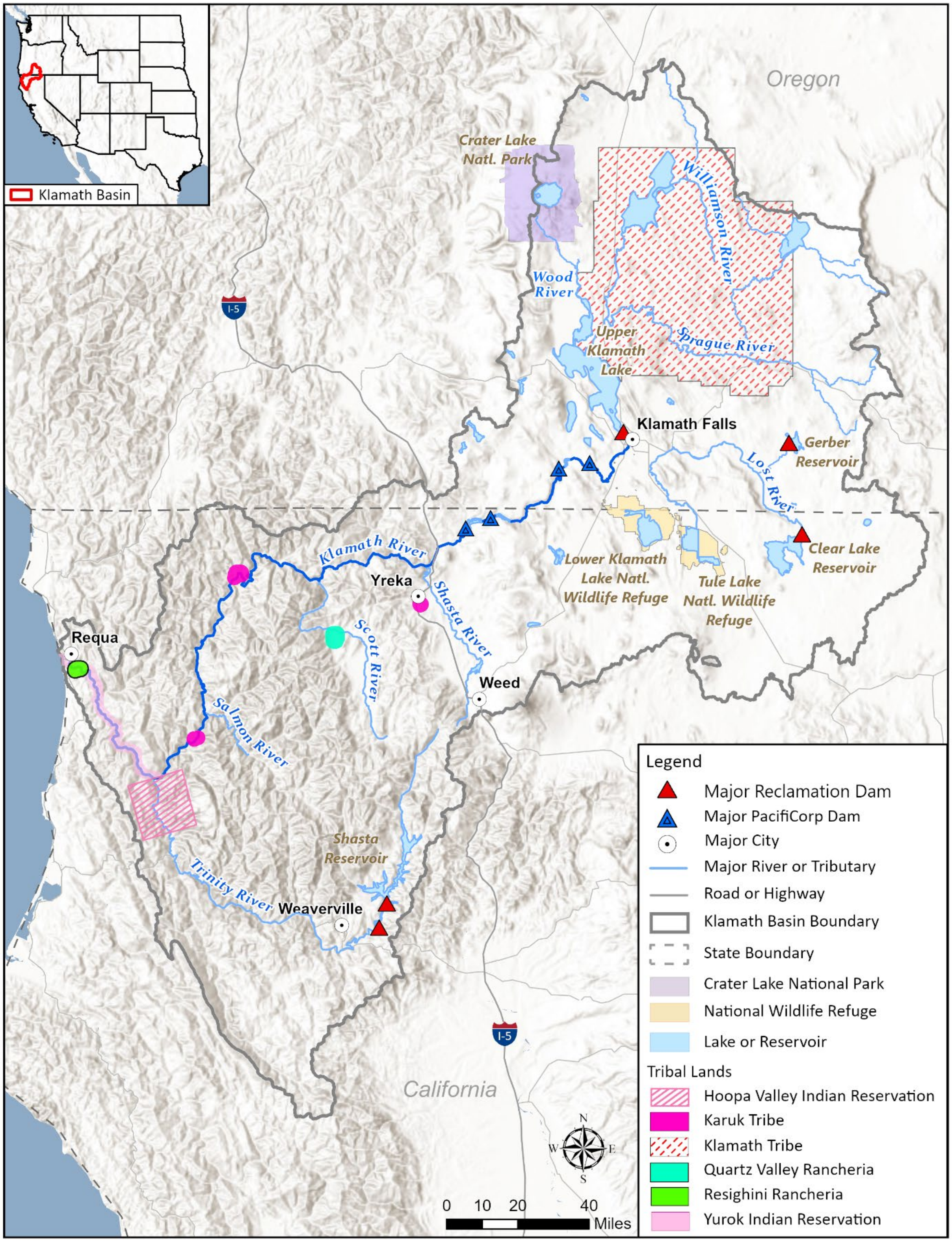



**Figure 1.—The Klamath River Basin.**

# C. Project Purpose and Overall Approach

The purpose of the current NFS is to use modern science, methods, and tools to develop revised natural streamflow estimates for the Klamath River Basin from water years (WY) 1981 through WY 2020. This study will estimate streamflow for current conditions and for pre-development conditions:

- **Pre-development Conditions** are defined as the landscape and hydrologic conditions that existed around 1900, prior to major development of the region for irrigated agriculture, forestry, and other purposes.

- **Current Conditions** are defined as the landscape and water demand conditions that occurred throughout the past four decades, as a result of land use, development, and water management practices.

Although natural streamflow is often defined as that which occurs in the absence of human intervention, for the purposes of this study, natural streamflow estimates are defined as those flows that would occur if pre-development conditions existed from WY 1981 through WY 2020. To this end, this study estimates daily natural streamflow from WY 1981 through WY 2020 at 12 locations within the Klamath River Basin under both pre-development and current conditions (table 1). For the purposes of this study, the Klamath River Basin was divided into three geographic regions, referred to as Phases (figure 1). The Phases are established based on current geographic domains of available surface and groundwater models. UKB comprises two of the three phases. Phase 1 includes all inflows to UKL such as the Wood River, Sprague River, and Williamson River, with the downstream boundary being Link River Dam. Phase 2 includes the UKB between Link River Dam and Iron Gate Dam. Phase 3 includes most of the Lower Klamath Basin, encompassing the contributing areas downstream of Iron Gate Dam to the Klamath River upstream of its confluence with the Trinity River. Table 1 includes a list of each of the natural flow locations defined by phase of their corresponding U.S. Geological Survey (USGS) gage site.

To develop natural streamflow estimates at the designated 12 locations, the NFS integrates six numerical modeling components through implementation of a mass balance model in RiverWare. A conceptualization of these different hydrologic processes and the modeled components of the NFS can be seen in figure 2. A basic description of each modeled hydrologic component is as follows:

1. The surface hydrology model quantifies recharge that results from distributed precipitation and the runoff component of streamflow. The distributed recharge and surface runoff output from the surface hydrology model is used as input into the groundwater model.

2. The groundwater modeling focuses on areas with substantial groundwater and surface water interaction and where groundwater pumping is known to occur. In the UKB, the

model simulates groundwater conditions and estimates groundwater levels, storage, pumping, drainage flow to tile drains, evapotranspiration, and flow between the UKB and neighboring basins. The baseflow to streams and seepage to and from lakes and reservoirs is used as inputs to the RiverWare mass balance model. In the LKB, groundwater modeling is focused on groundwater and surface water interactions in the Scott and Shasta River basins.

3. The evapotranspiration (ET) demands modeling estimates net ET (evapotranspiration minus precipitation), deep percolation recharge by agricultural users, and ET rates for groundwater dependent vegetation. The resulting ET estimates are added to or subtracted from the water budget in the corresponding models (i.e., deep percolation recharge is connected to the groundwater model). Consumptive use estimates are also used to calibrate the surface hydrology model.

4. The open water evaporation modeling quantifies open water evaporation rates and volumetric evaporation from lakes and reservoirs. These evaporation rates are used in modeling lakes and reservoirs in the RiverWare mass balance model and evaporation from UKL is used during calibration of the surface hydrology model.

5. Hydraulic modeling in the NFS analyzes the natural storage capacities, hydraulic controls, and interconnectedness of rivers, lakes, and wetlands in the basin after the removal of dams, railroads, etc. The hydraulic information will be used to represent these features in the RiverWare mass balance model and was also used to estimate average depths and pre-project open water surface areas in the open water evaporation modeling component.

6. The RiverWare mass balance modeling incorporates streamflow observations, direct output from the other models (e.g., baseflow contributions to streams, evaporation from lakes, etc.), hydraulic controls, lake and reservoir capacities, and other physical features of the river system to estimate natural streamflow at specific locations.

**Table 1.—List of Klamath NFS natural streamflow study locations (map of all USGS gages found at https://waterdata.usgs.gov/nwis/rt)**

| Phase | USGS site | Description |
|---|---|---|
| 1 | 11501000 | Sprague River near Chiloquin, OR |
| | 11502500 | Williamson River below Sprague River near Chiloquin, OR |
| | 11507500 | Link River at Klamath Falls, OR |
| | 11504115 | Wood River near Klamath Agency, OR |
| 2 | 11509500 | Klamath River at Keno, OR |
| | 11510700 | Klamath River below JC Boyle Powerplant near Keno, OR |
| | 11516530 | Klamath River below Iron Gate Dam, CA |
| 3 | 11517500 | Shasta River near Yreka, CA |
| | 11519500 | Scott River near Fort Jones, CA |
| | 11520500 | Klamath River near Seiad Valley, CA |
| | 11523000 | Klamath River at Orleans, CA |
| | Not Applicable | Klamath River at Weitchpec, CA |

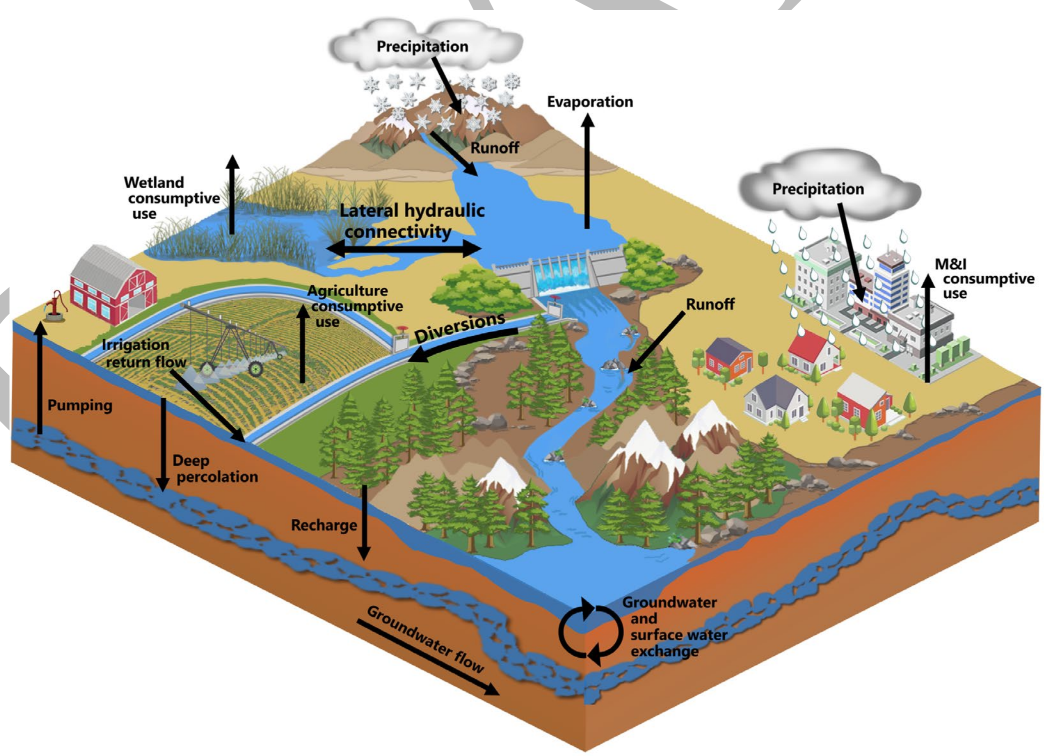



**Figure 2.—A conceptualization of the different hydrologic processes that are modeled in the Klamath Natural Flow Study.**

## D. Focus of Current Document

Given the complexity and numerous models that the NFS uses, each modeling component has an individual Technical Memorandum (TM) devoted to detailing the methodologies used to develop that component. This TM focuses on the development of daily open water evaporation rates and volumes from all lakes and reservoirs that have changed between pre-development and current conditions in Phase I and Phase II of the Klamath NFS. The processes represented in the open water modeling component are shown in figure 3 where they are highlighted in color while the rest of the conceptual image is in black and white.

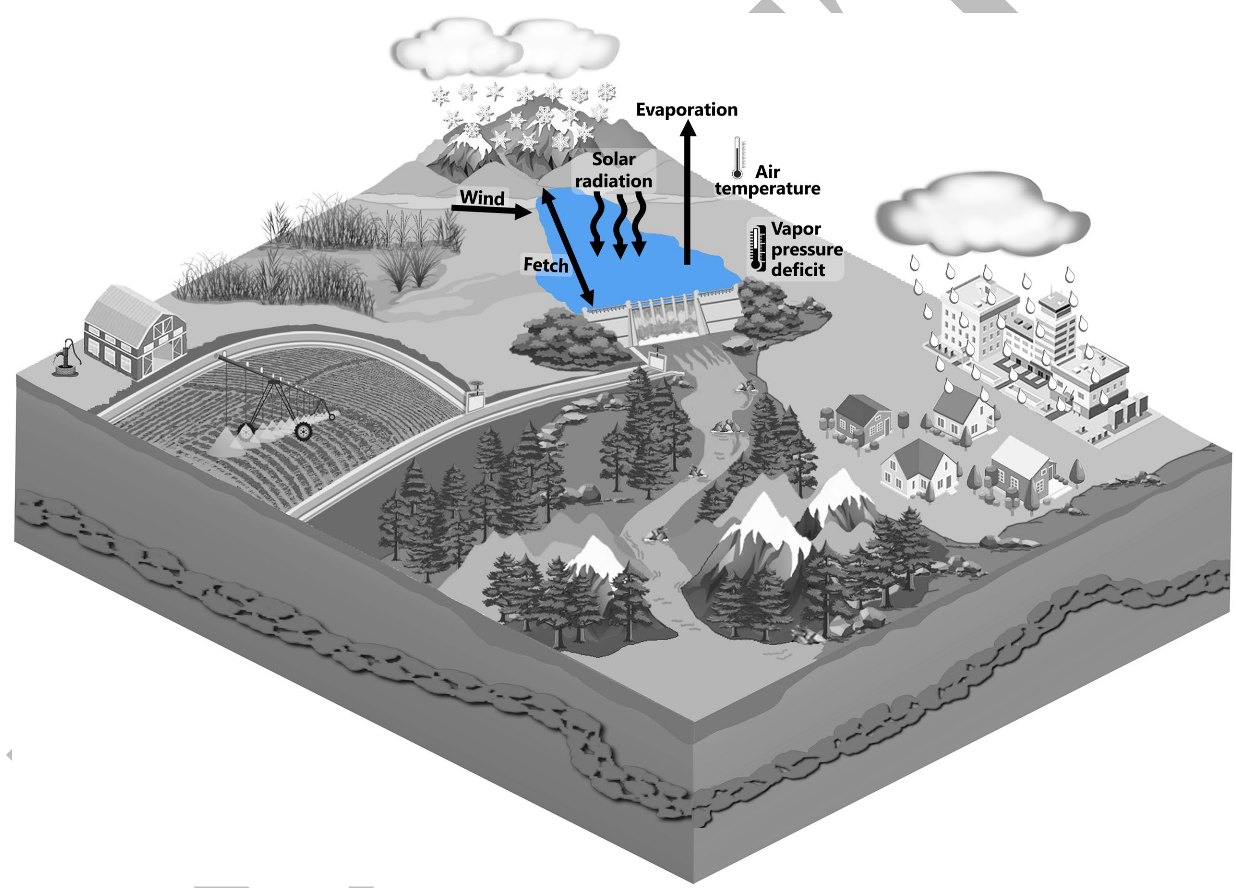



**Figure 3.—A conceptualization of the open water evaporation processes detailed in this report are shown in color while the remaining hydrologic processes modeled for the Klamath NFS are in black and white.**

UKB covers approximately 8,300 square miles (mi$^2$) and contains 12 different reservoirs or lakes and one conglomerate of reservoirs, that are modeled for the NFS (figure 4). These 12 waterbodies include four water supply reservoirs for the Klamath Project: UKL, Lake Ewuana, Clear Lake Reservoir, and Gerber Reservoir; two wildlife refuges: Lower Klamath and Tule

Lake National Wildlife Refuges (NWR); three Pacific Power Corporation (PacifiCorp) hydropower reservoirs: JC Boyle Reservoir, Copco 1 and 2, and Iron Gate Reservoir; and three reservoirs that are part of the trans-basin diversions from UKB to the Rogue Basin: Fourmile Lake, Hyatt Reservoir, and Howard Prairie Reservoir. In addition to these 12 larger waterbodies, the Lost River Basin contains many smaller reservoirs (e.g., Willow Valley Reservoir and Strawberry Reservoir) that are lumped together and modeled as one evaporative loss from that Basin.

UKL is the largest natural freshwater lake in Oregon at about 25 miles long and approximately 3 to 12 miles wide. In this study, Agency Lake, located north of UKL and connected by a narrow channel to UKL, is also considered part of UKL. The water level is regulated by a low dam that was constructed in 1917 which maintains water surface elevations between 4,136 feet (ft) and 4,143 ft (USBR datum). Water from UKL is used for irrigation of reclaimed agricultural land, regulated to enhance power generation farther downstream on the Klamath River, and used extensively by waterfowl. The maximum depth of UKL is around 50 ft in small, confined areas; however, most of the lake is shallower than 20 ft (Johnson 1985).

During the first half of the 20th century, extensive areas of wetlands associated with UKL and Agency Lake were diked, drained, and converted to agricultural uses (Boyle 1976). During the period of record considered in this study the open water extent and storage capacity of UKL changed several times (table A-1). On July 8, 2006, a dike along the southern extent of Wocus Bay failed, re-flooding the area once known as Caledonia Marsh. The area remained flooded until the dike was repaired on December 31, 2006. Other dikes were intentionally breached to restore ecological function in the Williamson River delta. On October 30, 2007, The Nature Conservancy breached dikes around the periphery of that portion of the Williamson River delta lying north of the Williamson River, and subsequent restoration efforts breached dikes around the delta lying south of the Williamson River in the fall of 2008 (Erdman, Hendrixson, and Rudd 2011). Each of these events changed the relationship between lake surface elevation and lake storage volume, which is accounted for in the computation of the UKL average depth estimates as explained below.

Gerber Reservoir was constructed as part of the Klamath Project in 1925 with the completion of a dam across Miller Creek. It provides water for irrigation, flood control, recreation, and fish and wildlife benefits. The reservoir is deep enough to develop a thermocline in the warmer summer months when stratification occurs (Johnson 1985).

Clear Lake Reservoir was also constructed as part of the Klamath Project in 1910 and resides in northern California. The reservoir was formed through the construction of Clear Lake Dam on the Lost River which subsequently reduced flows into Tule Lake for the purpose of agriculture. While Clear Lake Reservoir has a very large surface area of around 100 square kilometers ($km^2$), it is relatively shallow in depth and thus has a high rate of evaporation (Reclamation n.d.).

Howard Prairie Lake and Hyatt Reservoir are part of the Rogue River Basin Project which stores and transfers water to the Medford area for agricultural purposes. Hyatt Reservoir was constructed in 1923 after the development of a dam on Keene Creek. Hyatt Reservoir is relatively shallow with well mixed waters. Howard Prairie Lake is larger than Hyatt Reservoir and was created in 1958 by damming Grizzly Creek in the Klamath River watershed. The surface area of Howard Prairie is around 8 $km^2$ with a maximum depth of 80 ft and the reservoir can develop a deep thermocline during the warmer months (Johnson 1985).

Tule Lake NWR has two sumps that contain open water most years. Sump 1A is maintained as a permanent open-water body with minimum and maximum water elevations of 4,034 ft and 4,037 ft (USBR datum), respectively, due to the Endangered Species Act guidelines for Lost River and shortnose sucker habitat protection (Risley and Gannett 2006). Sump 1B is hydrologically connected to Sump 1A by a narrow, gated canal. Prior to the early 2000s, it was also managed as a permanent open-water body; however, in the 21st century it has been managed as both a seasonal wetland and a permanent open-water body (Risley and Gannett 2006). Even though Sump 1A and 1B are hydrologically connected, the water level in each sump can vary. It is important to note that periodic drying events and persistent groundwater depletion have also caused subsidence in the area and some areas the sumps might be slightly deeper than recorded in the area-capacity data.

Lower Klamath NWR is composed of five different land types: croplands, permanent wetlands, seasonal wetlands, uplands, and parcels that rotate between the previous four designations (U.S. Fish and Wildlife Service 2016). Croplands consist mostly of fields of grain and grass hay. During the winter these fields are flooded for pre-irrigation. Permanent wetlands are flooded year-round and depending on the year occupy up to 10,000 acres of the refuge. Three types of vegetation grow in these wetlands: some are rooted at the bottom of the wetland and have protruding vegetation above the water surface, other vegetation is floating plants, and the third type of vegetation is rooted in the bottom of the wetland with no protruding parts above the water surface. Seasonal wetlands contain similar vegetation as the permanent wetlands, but they are not flooded year-round. Flooding of seasonal wetlands occurs for at least 6 months of the year with two of those months during the growing season. Seasonal wetlands can occupy up to 16,000 acres of the refuge. Uplands consist mostly of sparse vegetation similar to a high desert, as only 850 acres out of 6,500 acres are allowed to receive irrigation (U.S. Fish and Wildlife Service 2016).

Fourmile Lake is a large natural lake located at the foot of Mount McLoughlin near the divide between the Rogue and Klamath River Basins. Fourmile is a very deep lake with minimal shallow areas and was enlarged after the construction of a dam in 1922. Natural outflow from the lake is into Fourmile Creek, but currently a considerable portion is diverted via the Cascade Canal over the divide towards Fish Lake.

The three PacifiCorp hydropower reservoirs (JC Boyle Reservoir, Copco 1 and 2, and Iron Gate Reservoir) were all built between 1912 and 1964 to enhance hydropower generation on the Klamath River, with smaller flood control objectives. JC Boyle is a small narrow reservoir of approximately 23 acres with a narrow southern end with depths over 40 ft and a much wider northern end with depths of 10 ft or less. Iron Gate Reservoir is much deeper and larger (~1000 acres) than JC Boyle and resides at the southern-most end of the hydropower reservoirs on the Klamath River. Copco 1 is similar in size to Iron Gate Reservoir and also contains deeper portions which can develop some stratification in summer months (PacifiCorp 2004). All the PacifiCorp hydropower reservoir dams are slated to be removed in 2023 and the subsequent years to restore fish passage to the Klamath River.

The Lost River Basin has hundreds of small, independently owned reservoirs throughout the basin. It is not feasible to model each of these reservoirs individually; however, their lumped evaporative contribution is significant. In order to account for these reservoirs and their impact on current conditions' evaporation, their remotely sensed area is summed together and Willow Valley Reservoir is used as a representative reservoir for modeling purposes, as further described below.

The overall objective of the open water evaporation modeling component is to provide daily open water evaporation rates and volumes for both pre-development and current conditions from WY 1981 through WY 2020 at selected reservoirs and lakes in Upper Klamath Basin. This objective is accomplished using the Daily Lake Evaporation Model (DLEM; Bingjie Zhao et al. 2023), which calculates open water evaporation on a daily timestep using a modified Penman Monteith approach to account for heat storage effects as a function of mean reservoir depth. Discussion on the methods used can be found in Section II, results focusing on current and pre-project conditions can be found in Section III, model sensitivities and uncertainties are explored in Section IV and V, and conclusions drawn from the study are available in Section VI.


Figure 4.—The modeled reservoirs and lakes in the Klamath Natural Flow Study. Waterbody areas are from the NHDPlus database and only include areas designated as 'perennial'. These areas are used in fetch estimates, not in surface area timeseries used to estimate current conditions evaporative volumes.

# E. Excluded from Study

There are a handful of smaller constructed reservoirs in the Sprague River Basin such as Hyde Reservoir and Campbell Reservoir that were initially considered in this study. The extent of these reservoirs, assuming full capacity, is approximately 2.13 $km^2$ (Buto and Anderson 2020). Assuming the highest annual evaporative loss of any modeled reservoir in the Klamath Basin (approximately 4.5 ft per year; see Results section below), the evaporation from the combined extent of these Sprague River Basin reservoirs only accounts for 0.001 percent of the average annual outflow from the Sprague River. Therefore, the evaporation from these reservoirs is not significant in the estimation of natural flows and is not considered in this study. In addition, natural lakes like Crater Lake are not modeled as they did not significantly change in their extent between pre-development and current conditions.

Average depth when simulating the evaporative losses from Tule Lake NWR is only determined from Tule Lake NWR Sump 1A area-capacity and long-term elevation data. While area-capacity information is available for Tule Lake Sump 1B, long-term elevation data is not. Therefore, the average depth used in simulations is only estimated from Sump 1A; however, open water areas from both sumps are used in the estimation of evaporation volumes from the NWR. Historically, the gate between Sump 1A and 1B is open and water surfaces in both sumps are approximately equal.

Before a dike was built, during spring runoff season, overflow from the Klamath River spilled southward into Lower Klamath Lake, creating 94,000 acres of marshlands and open-water that were ideal for waterfowl breeding (Robbins 2022). Pre-development open water evaporation modeling of Lower Klamath Lake does not include this overflow that created a vast expanse of marshland. Evaporation and transpiration from marshlands are different from open water evaporation and cannot be modeled appropriately with the DLEM model or any open-water evaporation model. Evaporation and transpiration from the overflow from Klamath River into Lower Klamath Lake during pre-development conditions is included in the evapotranspiration (ET) modeling component of the NFS and details on how those ET rates are estimated can be found in the respective report.

To give continuity between modeling components, one daily gridded dataset is chosen for all modeling components. GridMET (Abatzoglou 2013) is used as the daily climate dataset for all components of the study given its historical duration, resolution, and number of different available climate variables needed for specific models. The NFS will not investigate the uncertainty related to choice of gridded climate dataset by running each model with a separate set of gridded climate forcings. However, the sensitivity of the open water evaporation models to specific climate variables is investigated in Section IV below.

# II. Methods

Open water evaporation is an important component of the terrestrial water and energy balance, as lakes and reservoirs cover approximately 5 million $km^2$ of Earth's land area (Zhao, G., Li, Y., Zhou, L., Gao 2022). Lakes and reservoirs can lose a lot of water to evaporation due to the strong vapor pressure gradient at the water-atmosphere interface. The amount of water lost through evaporation depends on factors such as the surface area of the lake, the surrounding climate, and the bathymetry of the lake, among others.

Open water evaporation is difficult to measure in the field, and in-situ measurements typically rely on Class A pan-based measurements or eddy covariance (EC) flux stations (Friedrich et al. 2018). As Class A pan measurements lack heat storage dynamics and the complexities and cost associated with EC measurements can be limiting, modeling evaporation rates using physically based evaporation models has become useful for water management scenarios.

Many open water evaporation models are based on the Penman equation, which accounts for the effects of radiative and advective energy on evaporation rates (Penman 1948; Friedrich et al. 2018). However, lakes and reservoirs are able to store a substantial amount of energy during spring and summer due to the large specific heat capacity of water, which is then released during the fall and winter. These large fluctuations in heat storage impact the amount of energy available for evaporation. Recent advances in using the Penman equation to estimate open water evaporation include Zhao and Gao's (2019) 'equilibrium temperature' algorithm which estimates heat storage as a function of average reservoir depth. This new algorithm is implemented in what is termed the 'Lake Evaporation Model (LEM)' and also considers reservoir geometry, fetch, wind direction, and near-surface humidity to develop more accurate estimates of monthly open water evaporation rates.

In the LEM, evaporation is estimated using the Penman Combination equation, which is defined as:

$$E = \frac{s(R_n - \Delta U) + \gamma f(u)(e_s - e_a)}{\lambda_v (s + \gamma)} \qquad \text{[Eqn. 1]}$$

where E is the open water evaporation rate (mm·d−1); s is the slope of the saturation vapor pressure curve (kPa·°C−1); $R_n$ is the net radiation (MJ·m−2·d−1); ΔU is the heat storage changes of the water body (MJ·m−2·d−1); f(u) is the wind function (MJ·m−2·d−1·kPa−1); $e_s$ is the saturated vapor pressure at air temperature (kPa); $e_a$ is the vapor pressure at air temperature (kPa); λv is the latent heat of vaporization (MJ·kg−1); and γ is the psychrometric constant (kPa·°C−1). Please see (G. Zhao and Gao 2019) for further derivation of the equations used to estimate evaporation.

# A. Model

For this study, we are using a version of the LEM that considers daily fluctuations in lake depth and the subsequent impact on heat storage and calculates Equation 1 above on a daily timestep (Bingjie Zhao et al. 2023). The model is referred to as the 'Daily Lake Evaporation Model (DLEM)'. The two largest modifications to LEM involve how DLEM estimates fetch length (a term in the wind function, f(u)) and heat storage at a daily timestep. The fetch effect is the gradual humidification of air that occurs when a parcel of air moves from dry land across a water body due to the readily evaporating body of water beneath the air mass (Woolway et al. 2020). Fetch length is defined as the distance between two tangent lines on the outer edges of the reservoir that are parallel to wind direction (see figure 2 of Zhao and Gao 2019). Thus, fetch length can change drastically in irregular shaped reservoirs based on changes in wind direction. In DLEM, the daily fetch length, as estimated by the wind direction, is used in combination with the daily average wind speed to represent the effect of fetch on evaporation rates.

DLEM also considers daily changes in heat storage in addition to daily changes in fetch length. In DLEM, heat storage is directly proportional to lake depth, which fluctuates on a daily timescale. When the lake or reservoir is deeper than approximately 20 meters (m) or 65 ft, a constant depth of 20 m is used as incoming radiation does not penetrate below that depth. This allows for evaporation rates to vary based on daily changes in lake or reservoir depth, which can occur due to variable inflows, management strategies, or weather events.

As with any numerical model, it is important to note the limitations of the DLEM. The current version of DLEM computes daily changes in heat storage based on the current day's depth only. This means that large changes in daily depth, say related to operations, are not accounted for in the change in heat storage (because water depth in this equation is for a single day). One alternative to this approach would be to estimate daily changes in heat storage using the previous day's depth and water temperature with the current day's depth and water temperature. This advective heat storage limitation is not exclusive to DLEM; other modeling frameworks suffer from similar challenges. Future DLEM development will explore ways to make these adjustments to the change in heat storage term.

In this study, DLEM is run using reservoir characteristics derived from current and pre-development conditions from January 1, 1979 through September 30, 2020, where results from January 1, 1979 to September 30, 1980 are treated as model spin up and used to create initial conditions. Results from the DLEM runs focus on WY 1981 through WY 2020. A flow chart of all DLEM inputs can be found in Appendix A, figure A-1.



# B. Reservoir Characteristics

DLEM requires physical characteristics the lake or reservoir to represent site-specific conditions. These physical characteristics include reservoir elevation, average reservoir depth, and a shapefile outlining the lake or reservoir extent to estimate fetch. In this section, we describe how these physical properties are defined during current and pre-development conditions.

## 1. Current Conditions

### a. *Water Surface Area*

Constant water surface areas of each lake or reservoir under current conditions are pulled from the National Hydrography Plus High Resolution (NHDPLUS HR) dataset (Buto and Anderson 2020). These water surface areas are only used to determine the fetch length across each waterbody and are not used in evaporative volume estimations. Timeseries of water surface areas used in the estimation of current conditions evaporation volumes are describe in section II.1.c below. For the surface areas associated with the estimation of fetch, the lakes that have multiple sections such as Tule NWR and Lower Klamath NWR are subsetted according to the 'FCode' attribute of the NHDPLUS HR dataset, where the FCode defines whether the waterbody is intermittent or perennial. Only parts labeled as 'perennial' are included in the surface area of Tule and Lower Klamath NWRs. The NHDPLUS HR boundary of Willow Valley Reservoir is used to estimate fetch length for the Lost River Basin Reservoirs. As UKL has undergone four different lake configurations over the modeled duration, four different fetch lookup tables are generated based on the different configuration references in table A-1. In figure 4, UKL is shown in the 'UKL w/o Caledonia, Tulana, or Goose Bay' configuration. All other current conditions boundaries are shown in figure 4 and used to calculate fetch as a function of wind direction.

### b. *Average Depths*

Daily average depth for each reservoir is determined from a combination of area-capacity curves (ACAPs), observed water elevation timeseries if available, hydraulic modeling, and/or operational limits (table 2). Average depth is estimated by dividing the volume of the lake by the area for each observed water elevation if the appropriate data is available. The source of each ACAP that is used in this study can be found in table 2. All ACAPs are considered constant throughout the modeled duration except for UKL as the configuration of UKL has undergone significant changes over time. Four different UKL ACAPs are used to represent the different time periods of the lake extent (Appendix A, table A-1). In addition, dead storage below 4038.01 ft from the 2022 survey (Hollenback et al. 2023) was added back into the ACAP associated with each of the four historic UKL configurations.

Observed water elevation timeseries are available for UKL, Tule Lake NWR, Clear Lake Reservoir, Gerber Reservoir, and Howard Prairie and Hyatt Reservoirs. Observed daily elevation data from October 1,1980 to December 25, 2010 for Gerber Reservoir and Clear Lake Reservoir was recorded by Reclamation's Klamath Basin Area Office (KBAO) in daily operation reports (DOR; KBAO 1980). The elevation of each reservoir was recorded on an approximately monthly basis in the DORs with increased frequency starting around 1988. To create a continuous elevation timeseries, linear interpolation was used to fill in days between observations for any gaps. After December 25, 2010, continuous electronic daily records of reservoir elevation are available and can be downloaded from Reclamation's Hydromet website (Reclamation 2021c). Observed water elevations at Tule Lake NWR are recorded for Sump 1A in DORs by the Tulelake Irrigation District (TID; Tulelake Irrigation District 1986) and date back to 1986. Prior to 1986, DORs recorded by KBAO summarize Sump 1A observed water elevations. Water elevation timeseries from Sump 1B are not available and average depths for both Tule Sumps are estimated only from Sump 1A data. Observed water surface elevation timeseries for Howard Prairie and Hyatt Reservoirs were downloaded from Reclamations' Hydromet database (Reclamation 2022a). Observed water elevations from UKL were also recorded in DORs by Reclamations' KBAO and date back to 1980 (KBAO 2017). For these reservoirs that have known observed water elevation timeseries, only one current condition run is completed, as there is very little uncertainty surrounding the delineation of average depth.

Observed water elevation timeseries are not available for the PacificCorp reservoirs (JC Boyle, Copco 1, and Iron Gate). Instead, operational constraints are used to bound possible average depths for each reservoir (PacificCorp 2004). Three model runs are completed for each of the PacificCorp reservoirs to help understand the uncertainty associated with unknown average depth estimates. Each of these runs holds either the minimum, mean, or maximum average depth constant for the entire duration of the model run.

Similar to the PacificCorp reservoirs, there is no known observed water elevation timeseries for Lower Klamath NWR. Lower Klamath NWR is managed based on objective water levels for each area of the refuge (U.S. Fish and Wildlife Service 2016) which are targets the refuge tries to achieve depending on annual water deliveries. An area-weighted depth for the total refuge is determined based off the objective water level and total acres across the refuge for each section. Mean depth is then estimated for each parcel in the refuge based on translation of staff gage heights to North American Vertical Datum of 1988 (NAVD88) and then computed via LiDAR analysis with ArcGIS. Each parcel in the refuge is assigned to one of the five land types: grain, seasonal wetland, permanent wetland, upland, or rotating. Only the seasonal and permanent wetland areas and depths are used in the calculation of the mean area-averaged depth. The maximum and minimum depths of these areas are also used to bound the depth analyses for Lower Klamath.

Lake Ewauna also does not have observed water elevation timeseries and thus, depth ranges for Lake Ewauna are based off a hydraulic modeling effort conducted in 2021 that modeled high (1000 $ft^3/s$) and low (100 $ft^3/s$) flows into the lake (Reclamation 2021b). Water elevations are determined from these flows and a 2018 bathymetric survey of the lake. The recorded 2018 water level during the bathymetric survey was used to determine the mean average depth, while the high and low flow water elevations from the hydraulic modeling effort were used for maximum and minimum modeled water depths.

Water surface elevations are also not recorded for Fourmile Lake and the average depths used in this study are determined from bathymetry provided in the 1985 Atlas of Oregon Lakes (Johnson 1985) and the Standing Operating Procedures of Fourmile Lake (Reclamation 2012) which specified the heights at which the lake is maintained at during operation. The '50th percentile' or main model run assumed a full lake and sensitivity runs are then completed assuming a 10 ft and a 35-ft drop in water surface elevation. Given the deep contours of the lake, average depth does not change substantially, even with large decreases in lake levels. However, it is important to note that as the water level drops at Fourmile Lake, the average depth actually increases. This is due to the shallower contours of the lake residing along the outer edges, and as the lake drops in level, those shallower portions of the lake are no longer filled with water and thus the average depth of the lake increases despite a lower water level. This leads to the ‘full’ lake having the lowest average depth as compared to when the lake is 10 or 35 ft lower than full.

The smaller Lost River Basin Reservoirs are modeled with a shallow range of average depths given their size and classification as both intermittent and perennial reservoirs in the NHDPLUS HR database. There is little to no information on bathymetry or depths for these reservoirs and it is unlikely they are deep enough to develop stratification in the summer, a process that is known to influence reservoir evaporation rates. Given these limitations, the Lost River Basin Reservoirs are modeled with a range in average depths from 1 to 15 ft to incorporate the inherent variability among all these smaller reservoirs.

**Table 2.—Lake and reservoir characteristics under current conditions**

| Lake or reservoir | State | Observation period | Current conditions depth run(s) | Depth (ft)** | Area (ac) | Elevation (ft) | ACAP source | Water surface elevation source |
|---|---|---|---|---|---|---|---|---|
| Clear Lake Reservoir | CA | 1980–2020 | Observed Daily Timeseries | 7.7 | 19,055 | 4,480 | Ferrari [2009] | 1980 - 12/25/2010: DORs; Reclamation Hydromet thereafter |
| Copco 1 | CA | N/A | Low = Min Op. Elev. | 36.2 | 905 | 2,604 | PacificCorp. (2004). FERC Project No. 2082. | PacificCorp. (2004). FERC Project No. 2082. |
| | | | Mean = Mean Op. Elev. | 38.7 | 945 | | | |
| | | | High = Max Op. Elev. | 40.8 | 980 | | | |
| Fourmile Lake | OR | N/A | Low^ = Full | 45.1 | 960 | 5,744 | Johnson, D. (1985). Atlas of Oregon Lakes | Johnson, D. (1985). Atlas of Oregon Lakes and Reclamation SOP 2012 |
| | | | High = 35 ft below full | 50.7 | 380 | | | |
| | | | Highest = 10 ft below full | 53.8 | 567 | | | |
| Gerber Reservoir | OR | 1980–2020 | Observed Daily Timeseries | 18.6 | 2,455 | 4,821 | 1925 Reservoir Survey | 1980 - 12/25/2010: DORs Reclamation Hydromet thereafter |
| Howard Prairie Reservoir | OR | 1980–2020 | Observed Daily Timeseries | 25.8 | 1,570 | 4,527 | Reclamation CPN region office [2022] | Bureau of Reclamation Columbia-Pacific Northwest Region Hydromet. |

**Table 2.—Lake and reservoir characteristics under current conditions**

| Lake or reservoir | State | Observation period | Current conditions depth run(s) | Depth (ft)** | Area (ac) | Elevation (ft) | ACAP source | Water surface elevation source |
|---|---|---|---|---|---|---|---|---|
| Hyatt Reservoir | OR | 1980–2020 | Observed Daily Timeseries | 14.8 | 738 | 5016 | Reclamation CPN region office [2022] | Bureau of Reclamation Columbia-Pacific Northwest Region Hydromet. |
| Iron Gate Reservoir | CA | N/A | Low = Min Op. Elev. | 55.0 | 900 | 2,326 | PacificCorp. (2004). FERC Project No. 2082. | PacificCorp. (2004). FERC Project No. 2082. |
| | | | Mean = Mean Op. Elev. | 56.6 | 910 | | | |
| | | | High = Max Op. Elev. | 62.3 | 944 | | | |
| JC Boyle Reservoir | OR | N/A | Low = Min Op. Elev. | 9.4 | 160 | 3,792 | PacificCorp. (2004). FERC Project No. 2082. | PacificCorp. (2004). FERC Project No. 2082. |
| | | | Mean = Mean Op. Elev. | 9.8 | 205 | | | |
| | | | High = Max Op. Elev. | 12.3 | 220 | | | |
| Lake Ewauna | OR | Hydraulic modeling | Low = 1,000 $ft^3/s$ water level | 6.5 | 299 | 4,088 | 2018 bathymetric survey | Reclamation. (2021b) |
| | | 2018 | Mean = 2018 water level | 8.1 | 308 | | | |
| | | Hydraulic modeling | High = 10,000 $ft^3/s$ water level | 11.6 | 319 | | | |
| Lower Klamath NWR | CA | Depth: 2010–2016 GLEV area: 1984–2018 | Low = min. depth | 0.5 | approx. 2,000 to 9,000* | 4,078 | U.S. Fish and Wildlife Service, D. (2016) | U.S. Fish and Wildlife Service, D. (2016) |
| | | | Mean = mean depth | 1.9 | | | | |
| | | | High = max. depth | 3.6 | | | | |
| Tule Lake NWR | CA | 1980–2020 | Observed Daily Timeseries | 4.6 | 242 | 4032 | Topo Maps 12-D-983 & 984 (1986) | Klamath Basin Reclamation Area Office; Tulelake Irrigation District |
| Upper Klamath Lake | OR | 1980–2020 | Observed Daily Timeseries | 7.6 | 81,749 | 4,141 | Klamath Basin Reclamation Area Office [2017] | Klamath Basin Reclamation Area Office |
| Willow Valley Reservoir: AKA - Lost River Reservoirs | OR & CA | 2020 | Low | 1.0 | 3,954* | 4526 | Area Source: Buto, S. G., & Anderson, R. D. (2020). NHDPlus High Resolution. | |
| | | | Mean | 7.5 | | | | |
| | | | High | 15.0 | | | | |

*Area derived from GLEV dataset (B. Zhao et al. 2023).
^'Low' depth that represents the average Fourmile Lake depth when at full capacity, is the depth used in the main/best run.
**Depths and Areas for 'observed daily timeseries' are median depths and areas from WY 1981 to WY 2020. Note that 'Observed Daily timeseries depths vary on a daily basis, while low, mean, and high depth runs have a constant depth throughout the entire run.
***NWR = National Wildlife Refuge; Op. Elev. = operating elevation; min. = minimum; max. = maximum; ac. = acres; ft. = feet; $ft^3/s$ = cubic feet per second.

### c. *Area Timeseries*

Volumetric evaporation under current conditions is estimated by multiplying the simulated daily evaporation rate by a daily waterbody area. Daily timeseries of reservoir area are available for all the reservoirs that have observed daily depth data; however, the daily area observations do not account for ice cover during the winter months. Turbulent fluxes such as evaporation from lakes cease during ice-covered durations, even though conductive heat flow continues through the snow and ice (Brown and Duguay 2010). Therefore, for all reservoirs, an average monthly waterbody area is determined from the Global Lake Evaporation Volume (GLEV; Zhao, G., Li, Y., Zhou, L., Gao 2022) dataset, which runs from 1985 to 2018. Zhao et al. (2022) estimate average monthly waterbody area using a Landsat-based global surface water dataset (GSWD; Pekel et al. 2016) for all lakes in the HydroLakes database (Messager et al. 2016). Ice covered area is accounted for within the GWSD dataset and removed from the monthly surface areas by modeling the monthly fraction of ice duration using reanalysis air temperature and freeze/thaw lags.

The GLEV areal dataset accounts for different lake configurations over time, such as those observed at UKL. For example, each part of UKL, that at times is connected to the overall lake, has a different identification number in the HydroLakes dataset (Messager et al. 2016) and a monthly area timeseries associated with that portion of the lake. All area timeseries associated with UKL are then added together to calculate the overall areal extent of UKL. This is also the case with Lower Klamath NWR. The surface area from Tule Lake NWR includes surface areas from both Sump 1A and Sump 1B.

As waterbody area is needed from WY 1981 to WY 2020 and the GLEV dataset begins in 1985 and ends in 2018, monthly averages are estimated from the adjacent five years of data due to the high interannual variability observed in waterbody areas (figure A-3). For instance, to fill in monthly waterbody area from 2019 through WY 2020, monthly averages are determined from the previous five years of data (2014 through 2018). To fill in WY 1980 through 1984, monthly averages from 1985 through 1989 are assigned. Disaggregation from monthly waterbody area to daily waterbody area is accomplished by assuming waterbody area is constant for each day of the month.

Given the aggregated nature of modeling evaporation loss from the Lost Basin reservoirs, a constant daily average area is used to estimate the daily volumetric evaporation loss from these waterbodies. It is not possible to use the GLEV area dataset (Zhao, G., Li, Y., Zhou, L., Gao 2022) for all of the waterbodies in the Lost Basin as GLEV only incorporates waterbodies over 10 hectares in area; many of the 132 reservoirs identified in the Lost Basin were less than 10 hectares. Using the NHDPlus High Resolution dataset (Buto and Anderson 2020) it is determined that the total area of the 132 small independent reservoirs in the Lost Basin is approximately 33 $km^2$. Out of the 132 reservoirs, perennial reservoirs covered 16 $km^2$; intermittent reservoirs covered 13 $km^2$, and marsh/swamp waterbodies covered 4 $km^2$. For the volumetric calculations, only the area of the perennial reservoirs is used due to the unknown nature of the intermittent reservoirs. As there was no information as to the fluctuations in water surface elevation for each of these reservoirs, a constant 16 $km^2$ is used to estimate volumetric evaporation from WY 1981 through WY 2020.

# 2. Pre-development Conditions

Pre-development simulations of open water evaporation rates and volumes are performed as part of the Klamath NFS and intended to represent hydrometeorological conditions in the basin between WY 1981 and WY 2020, where development impacts have been removed. By utilizing the same forcing time period (i.e., gridded climate data from WY 1981 and WY 2020), we are able to estimate how the building of reservoirs and dams, the draining of wetlands and shallow open water areas, and agriculture, may have influenced open water evaporation estimates in the basin. In this section, we describe specific changes to the open-water modeling framework used to reflect man-made influences on open water evaporation.

## a. *Selection of Pre-development Lakes*

Only six of the thirteen modeled waterbodies are natural and present before development in the Klamath Basin (figure 5 and table 3). These natural lakes include: Upper and Lower Klamath Lakes, Lake Ewauna, Tule Lake, Fourmile Lake, and Clear Lake. Upper Klamath Lake is Oregon's largest natural lake in area, although it is fairly shallow in depth. In 1921, construction on the Link River Dam was completed and moderated outflow from UKL. UKL used to flow into Link River, a short stream that emptied into Lake Ewauna, the true headwaters of the Klamath River. Before the railroad was built, during spring runoff season, overflow from Klamath River spilled southward into Lower Klamath Lake, creating 94,000 acres of marshlands and open water that were ideal for waterfowl breeding (Robbins 2022). Pre-development open water evaporation modeling of Lower Klamath Lake does not include this overflow that created a vast expanse of marshland. Evaporation and transpiration from marshlands are different from open water evaporation and cannot be modeled appropriately with the DLEM model. However, the ET occurring from this large expanse of marshland created by the overflow from Klamath River IS included in the Evapotranspiration component of the NFS, please see that report for details. Pre-development open water evaporation modeling of Lower Klamath Lake, will, however, include the larger surface area based off historical maps (Lippincott, Murphy, and Humphreys 1905).

Beginning in 1905, much of Lower Klamath Lake and Tule Lake and surrounding wetlands were drained for agricultural purposes. Clear Lake Reservoir was created in 1910 with the construction of a rockfill dam that also reduced flows into Tule Lake while providing irrigation water to farmers in the Lost River Basin. Prior to the pumping of water over to Lower Klamath NWR, Tule Lake was the terminus of the closed Lost River Basin which begins at Clear Lake. Despite being the terminus of a closed basin, Tule Lake was not saline likely due lake seepage into the groundwater system on the south end (Risley and Gannett 2006). The pre-development surface area of Tule Lake at low water levels was similar to that of UKL and at high water levels was approximately 40% larger in area than UKL.

Fourmile Lake was a large natural lake located at the foot of Mt. McLoughlin, just northwest of UKL. The outflow from Fourmile Lake flowed south into Fourmile creek, but after the construction of a dam at the outlet of the lake in 1922 and the completion of the Rogue River Basin Project, a considerable portion of the outflow from the lake is now diverted to the Cascade Canal and over into the Rogue River Basin (Atlas of Oregon Lakes 1985). The impoundment of Fourmile Lake approximately doubled the surface area of the natural lake.

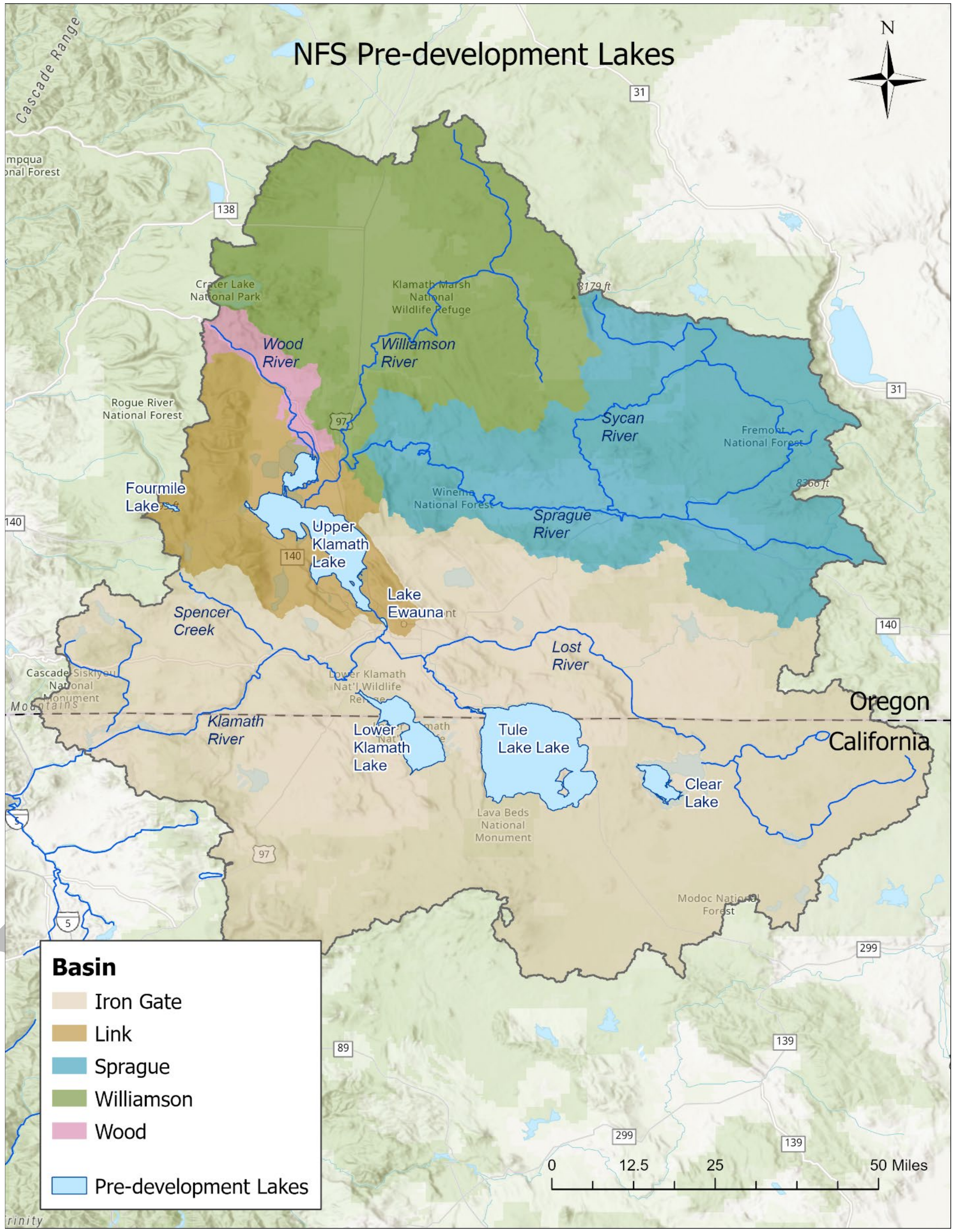



**Figure 5.—The high-water extent of natural lakes in the Upper Klamath Basin before development began.**

**Table 3.—Pre-development lake characteristics and sources of data**

| Lake | Relative Water Surface Elevation | Type of Elevation | Elevation Source | ACAP source | Elevation (ft) | Area (ac) | Average Depth (ft) |
|---|---|---|---|---|---|---|---|
| Clear Lake | High | Historical estimation | Lippincott et al., 1905 | Lippincott et al., 1905 and Reclamation, 2009 | 4,523.0 | 15,830 | 4.6 |
| | Low | Historical estimation | Voorhees et al., 1913 | | 4,518.5 | 8,000 | 2.0 |
| Fourmile | High | Natural River Sill | Reclamation, 2012 | Johnson 1985 | 5,729.0 | 492 | 56.4 |
| Lake Ewuana | High | Historical estimation | Lippincott et al., 1905 | Reclamation, 2021 | 4,087.0 | 327 | 7.2 |
| Lower Klamath Lake | High | LKL WSE historical flood estimation | Reclamation, 2005 | Lippincott et al., 1905 | 4,089.9 | 27,125 | 9.8 |
| | Low | Keno Reef Minimum Elevation | Pacific Power & Light Company, 1965. | | 4,084.9 | 27,050 | 4.6 |
| Tule Lake | High | Historical estimation | Abney, 1964 | Lippincott et al., 1905 | 4,065.9 | 102,711 | 24.3 |
| | Low | Historical estimation | Abney, 1964 | | 4,038.9 | 52,874 | 2.7 |
| Upper Klamath Lake | High | Historical estimation | Dicken & Dicken, 1985 | Reclamation, 2023 to Putnam's Point Reef | 4,145.0 | 66,085 | 10.8 |
| | Low | Historical Putnam's Point reef | Neuman, 2009 | | 4,139.2 | 65,077 | 5.2 |

**Elevations are NAVD88 datums. ft = feet; ac = acres.*

### b. *Average Depths*

No time-series data of water surface elevation exists for the pre-development lakes in the Upper Klamath Basin. Literature and geologic controls are used to determine possible bounds of pre-development water surface elevation at each of the pre-development lakes (table 3). A detailed description of the pre-development ACAP relationships and their uncertainty can be found in the Klamath Natural Flow Study Hydraulic Modeling – Phase 1 & 2 report. A short summary is presented here.

The pre-development ACAP conditions of UKL are developed using the current conditions ACAP in combination with historic evidence based on literature, historical maps, and topographic analysis. Based on a lack of detailed historical bathymetry for the entire lake, the bathymetry from current conditions is used for the pre-development open-water extent of UKL except for the reef at Putnam's Point. In pre-development conditions, Putnam's Point reef defined the downstream boundary of the UKL ACAP in comparison to the current conditions analysis, which used the Link River Dam.

Pre-development ACAP relationships for LKL are calculated based on United States Reclamation Service 1905 topographic and irrigation map of the 'Upper and Lower Klamath Projects' (Lippincott, Murphy, and Humphreys 1905). The map includes depth measurements and 1-ft contours within the open water body of Lower Klamath Lake. Using the elevation contours within the LKL open water extent on the 1905 map, an initial investigation into the lakebed found that subsidence has occurred likely due to wetland removal and agricultural development. In some locations the subsidence is greater than 10 ft. Therefore, it is determined that recent lidar datasets are not an accurate representation of available storage in LKL under pre-development conditions. The 1905 map provided the best available data for pre-development LKL volumes. As LKL was surrounded by broad tule wetlands in pre-development conditions, it is important to note that only the open water lake bathymetry is used for the average depth calculations and omits any areas of surrounding wetland. The low and high open water surface areas for LKL are relatively similar (i.e., within approximately 5 ft) as there is a feedback system between Klamath River and LKL during pre-development conditions that likely led to the water surface of LKL being relatively stable (see Hydraulics report for more detail). In pre-development conditions, low water elevation is controlled by Keno Reef, which creates a backwater control of both Klamath River and LKL water elevations (Voorhees, Hopson, and Patch 1913). Low LKL water elevations will be moderated by a greater amount of Klamath River water flowing into LKL, while high LKL water elevations will be moderated by greater amount of LKL water flowing into the Klamath River.

Like the LKL ACAP, the Tule Lake ACAP for the pre-development condition is created with the same 1905 topo-bathymetric map (Lippincott et al. 1905). For Tule Lake, the map also includes depth measurements and 1-ft contours within the open water body. Reclamation digitized the 1-ft contours and produced a triangular irregular network (TIN) to represent the bottom surface of pre-development Tule Lake. Historic fluctuations in water surface are for Tule Lake were quite significant; Tule Lake was reported to rise nearly 15 ft over a span of a few years (Dicken & Dicken 1985). Reports suggest that the lake surface rose considerably in years that the Klamath River overflowed into the Lost River Slough (Abney 1964; Voorhees, Hopson, and Patch 1913). These reports of water surface area are used to estimate high and low pre-development water levels for Tule Lake.

The pre-development ACAP for Lake Ewauna is developed using the current conditions bathymetry (Reclamation 2021b). The 1905 historic map (Lippincott, Murphy, and Humphreys 1905) only provides a few depths throughout the lake which is not enough for an area-capacity analysis.

Clear Lake was enlarged during development of the Klamath Project. In 2007, a bathymetric survey of Clear Lake Reservoir was completed by TSC (Reclamation 2009). Based on the bathymetric survey, an ACAP table was developed. This includes the portion of the lake that was mapped as inundated in the 1905 map (Lippincott, Murphy, and Humphreys 1905). The 2007 ACAP relationship is used in conjunction with the outlined area of Clear Lake in the 1905 map to calculate the average depth of Clear Lake in 1905.

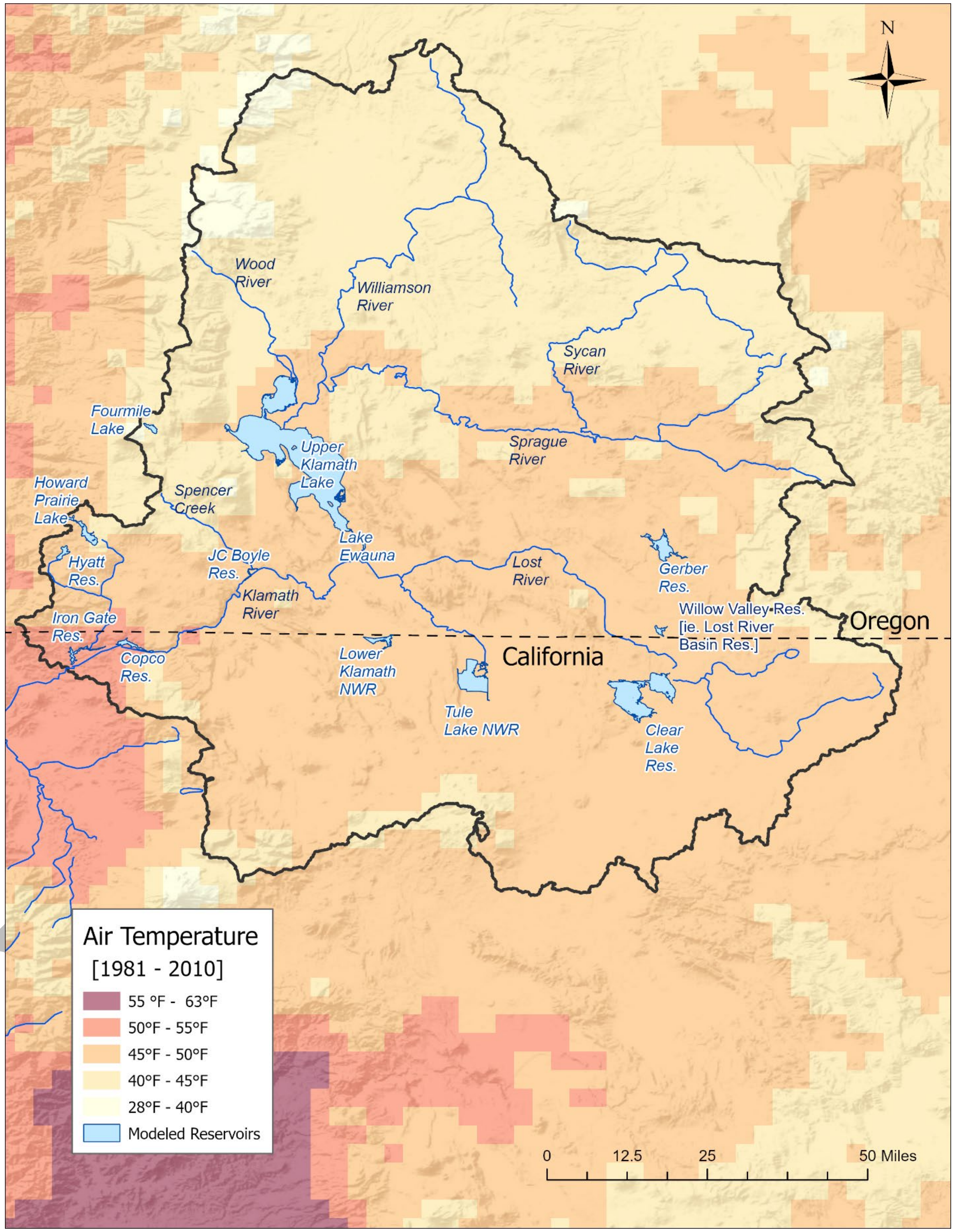
Fourmile pre-development average depth is determined from the 1985 bathymetric map of the lake (Johnson 1985) and by assuming that the full pool elevation of Fourmile Lake corresponded to the natural river sill at 5,729 ft, as specified in the Standing Operating Procedures for Fourmile Lake (Reclamation 2012).

## C. Forcing Data

The meteorological forcing variables required to run DLEM include downward shortwave radiation, average air temperature, wind speed, vapor pressure deficit, wind direction, and atmospheric pressure. All these variables except for atmospheric pressure are acquired from the Gridded Surface Meteorological (gridMET; Abatzoglou 2013) dataset, which is a daily surface meteorological dataset at a 4 kilometer (km) spatial resolution. Average air temperature and average relative humidity are calculated from the mean of daily maximum and minimum temperature and maximum and minimum relative humidity respectively. gridMET data is then processed from a 4 km grid resolution and spatially-averaged across the current condition surface area of each lake and reservoir as determined from the NHDPLUS HR dataset (Buto and Anderson 2020). Spatially-averaged climate data over UKL is estimated from the ‘UKL w/o Caledonia, Tulana, or Goose Bay’ configuration and spatially-averaged climate data for the Lost River Basin Reservoirs is estimated over the area of Willow Valley Reservoir.

As gridMET does not include atmospheric pressure, the variable is estimated using the ASCE equation (ASCE-EWRI 2005) and reservoir elevation. Atmospheric pressure is assumed constant over current and pre-development conditions.

Figure 6 shows the average annual air temperature over Klamath Basin and figure 7 shows the average daily incoming solar radiation over the basin. Average annual air temperature ranges from around 55 degrees Fahrenheit (°F) near Iron Gate Reservoir to around 30 °F near Fourmile Lake. In UKB solar radiation is highest in the south and eastern parts, with Gerber Reservoir receiving a daily average of 211 Watts per square meter (W/m$^2$) while waterbodies in the western part of the basin, such as Fourmile Lake, receive an average of 202 W/m$^2$ of solar radiation each day.




700 **Figure 6.—30-year average annual air temperature (˚F) from 1981 to 2010 over the Klamath**
701 **Basin.**
702

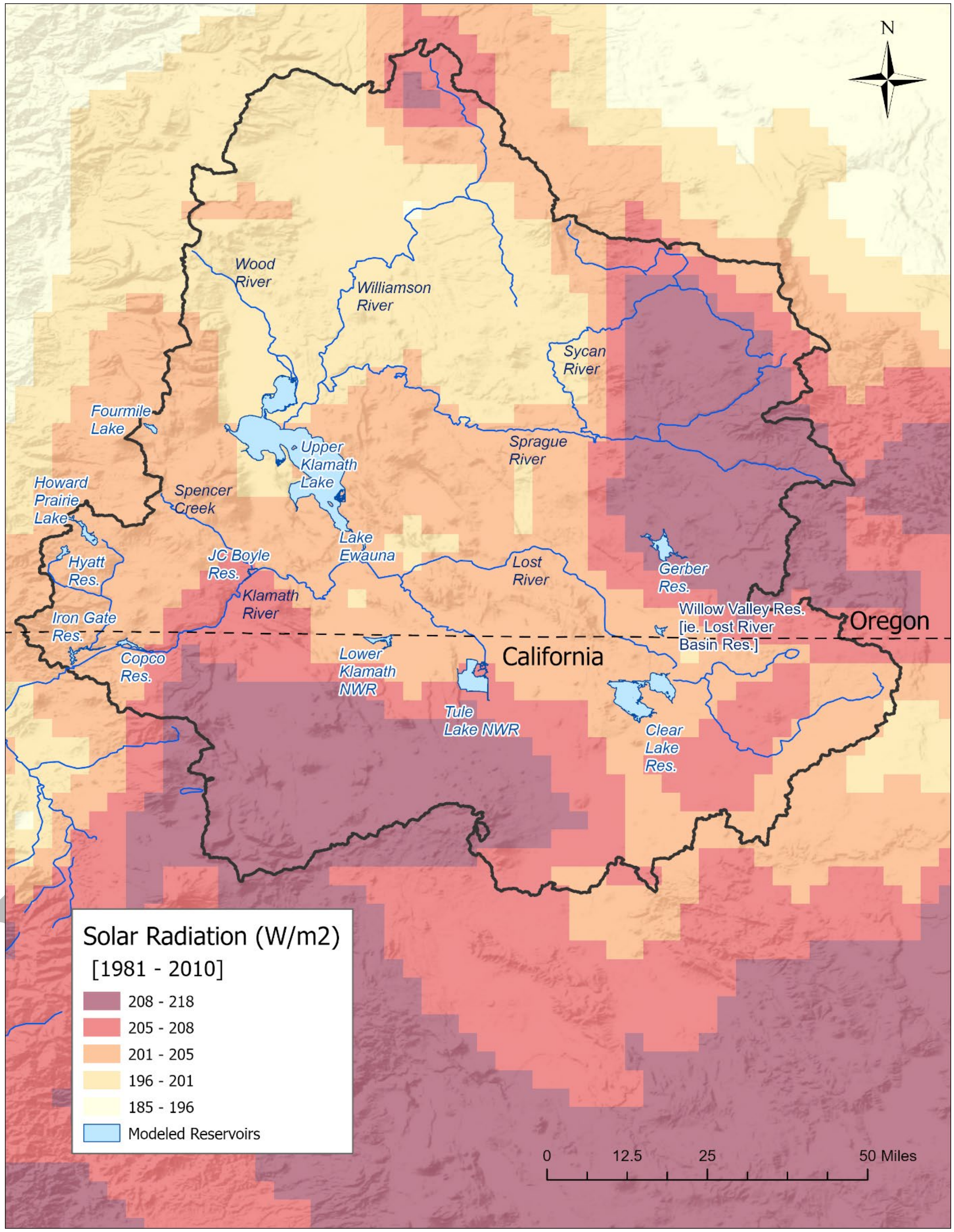



**Figure 7.—30-year average daily solar radiation (W/m2) from 1981 to 2010 over the Klamath Basin.**

# III. Results

The DLEM is run from January 1, 1979 to September 30, 2020, with results focusing on WY 1981 through WY 2020 for each of the 13 lakes and reservoirs modeled in the NFS. In this section, results focus on modeling evaporation under current conditions at observed average depths or depth ranges. Following the current conditions results, pre-project results are presented where pre-project average depths and areas are used to simulate open water evaporative losses. All results presented are water year totals, however, figure axes are often labeled as 'annual' for clarity and thus for the purpose of this report, annual refers to a WY total or average.

## A. Current Conditions

### 1. Open Water Evaporation Rates

Average daily evaporation rates for the current conditions mean/observed run are shown in figure 8. Average daily evaporation rates range from a minimum of -0.009 inches per day (in/day) to maximum of 0.053 in/day depending on the time of year and the reservoir. DLEM is able to simulate negative evaporation which represents the process of condensation. Condensation can form on the surface of a lake when the water temperature is colder than the ambient dewpoint temperature. The mean range in average daily evaporation rates between the 5th and 95th percentile is lowest at Fourmile Lake at approximately 0.0073 in and highest at Iron Gate Reservoir at approximately 0.01 in. Average daily evaporation rates appear to have the largest variability in the spring months and the lowest variability in the winter months.

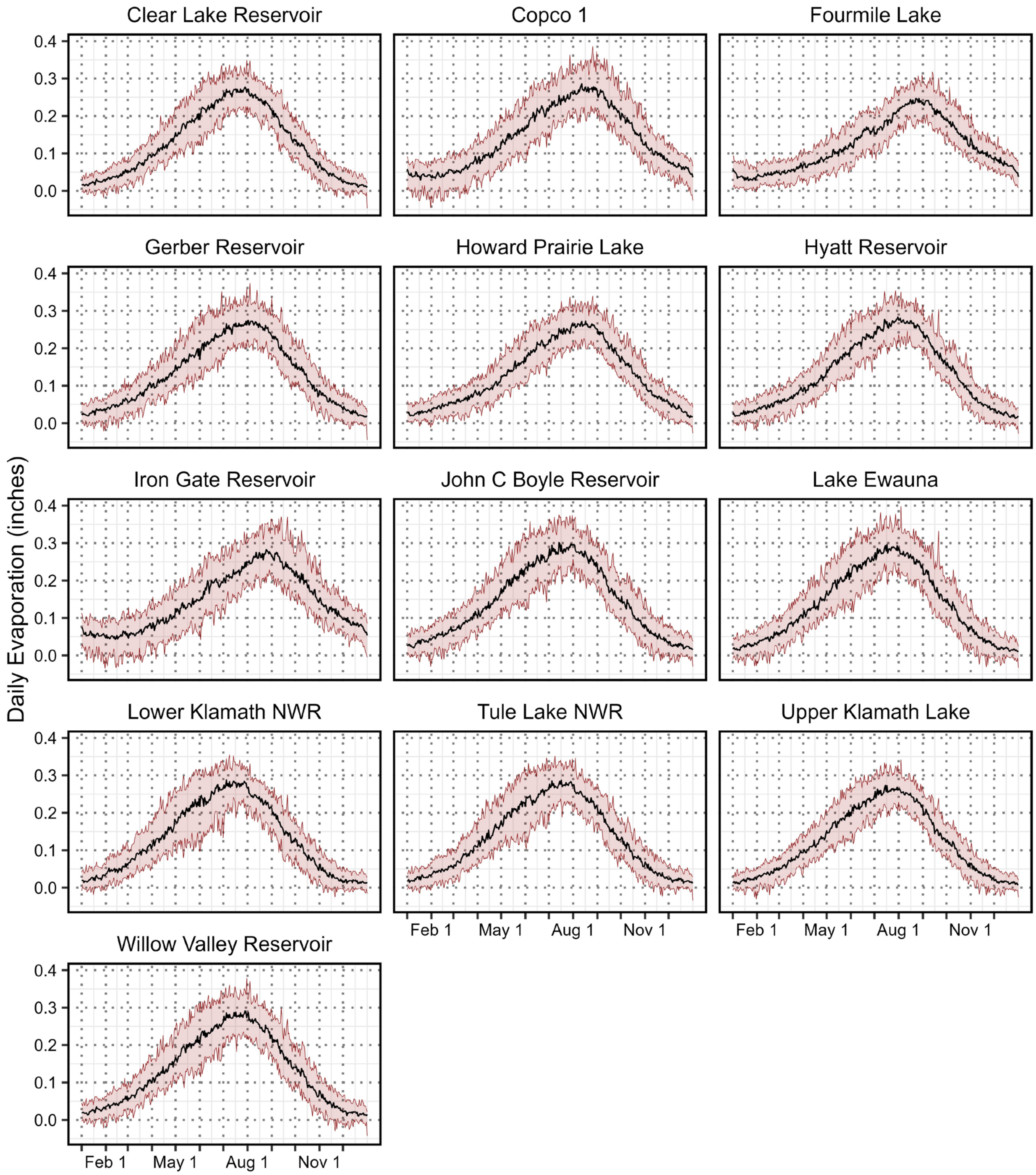



**Figure 8.—The distribution of average daily evaporation rates from WY 1981 through WY 2020 for the observed/mean run under current conditions. For Fourmile Lake this is the 'Full-Low Depth' run. Red shading indicates the 5th and 95th percentiles of daily evaporation rates modeled from WY 1981 through WY 2020, while the black line indicates the median value.**

Differences in average daily evaporation rates across the depth runs can be seen in figure 9. Larger differences due to reservoir depth occur in the cooler months, where evaporation rates are small, while depth has less of an influence on average daily evaporation rates in the summer or warmer months. As a reservoir or lake increases in depth changes in heat storage impact daily evaporation rates. The deeper the waterbody, the longer it takes to warm up the water in the spring and summer and thus evaporation rates are lower than a shallower waterbody. However, those deep-water layers store extra heat and can release it in the form of evaporation during the fall and winter months, leading to higher daily evaporation rates for the deeper waterbodies than the shallower waterbodies during this time of year. The results in figure 9 show this phenomenon as the low depth runs have higher evaporation as compared to the mean/observed depth run from spring to mid-summer and then lower evaporation in the fall and early winter. The higher depth runs show the opposite pattern, where evaporation rates are smaller from the early winter through mid-summer and then larger from mid-summer through early winter.

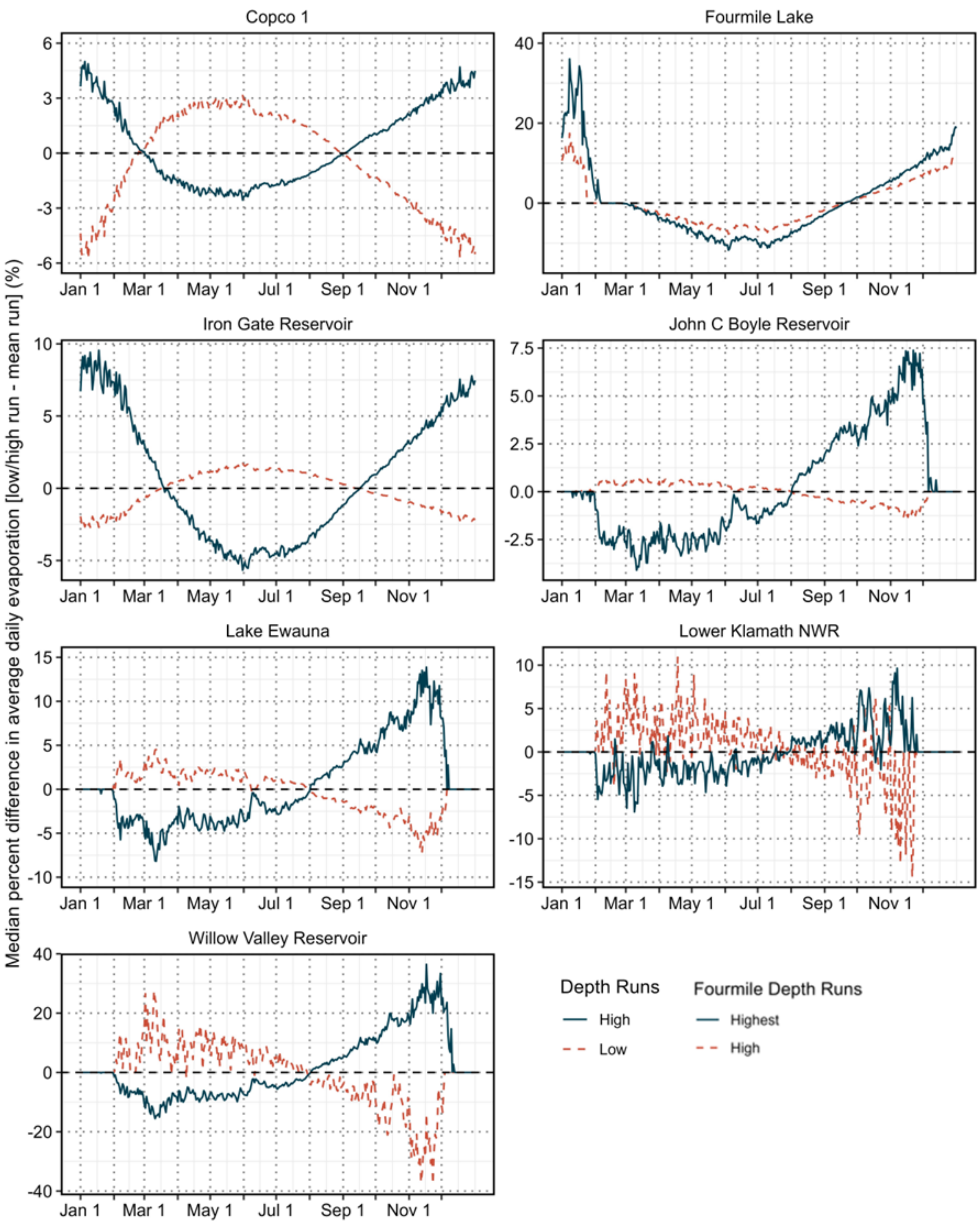



**Figure 9.—The median percent difference in average daily evaporation rates between the mean run and the low depth run (solid blue line) or the high depth run (dashed red line) from WY 1981 through WY 2020, computed as the (low/high depth run minus the mean depth run) divided by the mean depth run under current conditions. Fourmile Lake includes the low depth run (which is when the lake is full) to the high (solid blue line) and highest (dashed red line) depth runs.**

Mean monthly evaporation rates for each reservoir and depth uncertainty run can be seen in figure 10. Mean monthly evaporation peaks in July for the shallower reservoirs with depths less than approximately 12 ft (Clear Lake Reservoir, JC Boyle, Lake Ewauna, Upper Klamath Lake, Willow Valley Reservoir, and Lower Klamath and Tule Lake NWRs) and August for the deeper reservoirs with depths over 25 ft (Copco 1, Fourmile Lake, Howard Prairie Lake, and Iron Gate Reservoir). Mean monthly evaporation in reservoirs that have depths around 15 to 20 ft have similar peak monthly evaporation in both July and August (Gerber and Hyatt Reservoir).

Reservoir depth influences monthly evaporation trends, with the low depth runs exhibiting higher evaporation than the mean depth run during the spring months, while high depth runs have more evaporation than the mean depth run during the fall months. This trend is more pronounced in the Willow Valley Reservoir where depth was varied by up to 14 ft and evaporation rates could change by up to 30 percent in the month of November between the mean and maximum depth run. All other reservoirs, where variations in depth are based off of operational levels or objective water levels, have much smaller variations in monthly evaporation rates due to changes in depth. For instance, Iron Gate Reservoir operates between an average depth of 55.0 ft to an average depth of 62.3 ft. The largest difference in mean monthly evaporation rates at Iron Gate between the maximum and the minimum operating level is 12.5 percent in the month of January when evaporation rates are around 1.7 in per month.

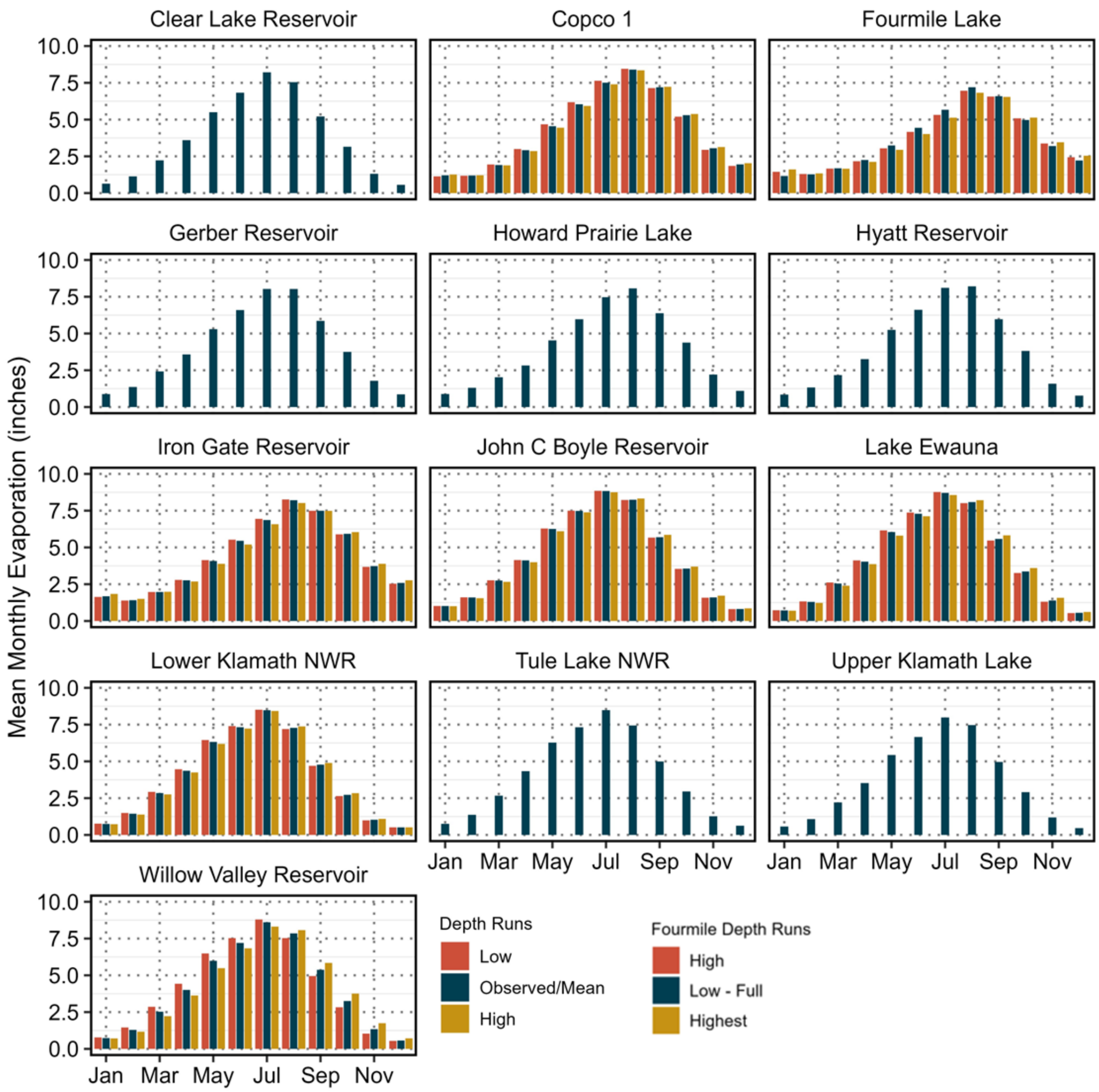



**Figure 10.—Mean monthly evaporation for each depth run from WY 1981 through WY 2020 under current conditions.**

Changes in reservoir depth do not influence annual evaporation rates to the same extent as they influence daily and monthly rates (figure 11). For instance, median annual evaporation rates for Copco 1 vary by less than a tenth of an inch between the lowest operational level (low depth run) and the highest operational level (high depth run). Willow Valley Reservoir has the largest difference in median annual evaporation rates between the 1-ft depth run (low depth run) and 15-ft depth run (high depth run) of 0.75 in.

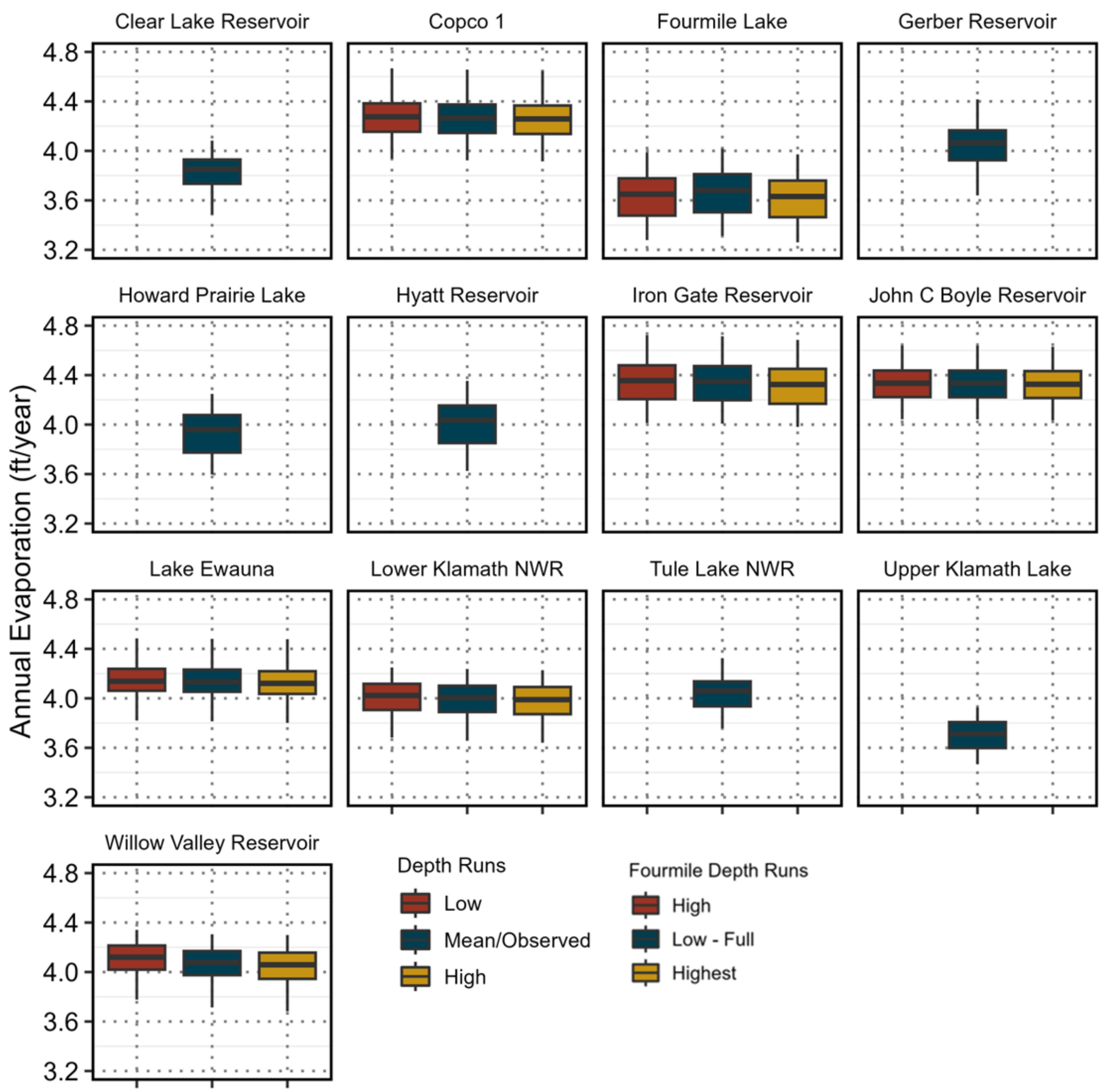



**Figure 11.—The distribution of annual open water evaporation rates from WY 1981 through WY 2020 for all modeled lakes and reservoirs in Upper Klamath Basin grouped by depth model run under current conditions. The box limits correspond to the 25th and 75th quartiles and the horizontal line within the box represents the median. Whiskers extend to 1.5 ± the interquartile range. Outliers are represented by black filled circles.**

### a. *Model Validation of Evaporation Rates*

Only a select number of field observations are available to compare the DLEM results to in order to assess model performance. A USGS study from 2013 investigated wetland and open-water evaporation at multiple sites around UKL (Stannard et al. 2013). Open-water evaporation from UKL was measured using the Bowen-ratio energy balance method at two locations across the lake during the warmer months of 2008–2010. The Bowen-ratio energy balance method employs an energy balance equation that uses net radiation, net advected energy (relates flow into and out of the lake with water temperatures), energy transferred to the lakebed (which can be estimated by lakebed temperatures, changes in energy storage within the lake (estimated by average water temperatures), and the Bowen ratio (estimated using water and air temperature and vapor pressure). The majority of these parameters were measured from two floating meteorological stations and streamflow gages.

Figure 12 displays the total evaporation estimated from the Bowen-ratio energy balance method at two different sites compared to the modeled DLEM evaporation during the same two-week periods, while table 4 gives the associated model error statistics. DLEM compares extremely well to the UKL evaporation estimates from Stannard et al. (2013). DLEM has an overall positive percent bias (computed as simulated minus observed divided by observed) and tends to overestimate evaporation by 2.1 percent. In 2008, DLEM appears to overestimate evaporation in all months except October, while in 2009 and 2010, DLEM appears to overestimate more during the summer months and underestimate evaporation during the spring and early fall months. Given that the DLEM model is constructed to simulate a reservoir- average evaporation rate, and the USGS energy budget estimates are computed for portions of the lake using meteorological forcings from individual sites, some differences across estimation methods are to be expected.

**Table 4.—Statistical comparison of DLEM current conditions results to observed field studies.**

| Reservoir or lake | Field study | Measurement duration | Year | Average MAE (inches/day) | Percent bias (%) |
|---|---|---|---|---|---|
| Upper Klamath Lake | Stannard et al., 2013 | Two weeks | 2008 | 0.014 | 4.6 |
| | | | 2009 | 0.015 | 5.1 |
| | | | 2010 | 0.015 | -1.5 |
| | | | Combined | 0.015 | 2.1 |
| Clear Lake Reservoir | Reclamation, 2021a | Monthly | 2018 | 0.043 | 19.5 |
| | | | 2019 | 0.052 | 12.7 |
| | | | Combined | 0.048 | 15.1 |
| Gerber Reservoir | Reclamation, 2021a | Monthly | 2018 | 0.063 | 30.9 |
| | | | 2019 | 0.026 | 12.3 |
| | | | Combined | 0.049 | 23.9 |

*MAE = Mean absolute error; percent bias = 100*sum[(simulated-obs)/sum(obs)]

**For comparison statistics to the UKL Stannard 2013 study, MAE is calculated using data from both sites.

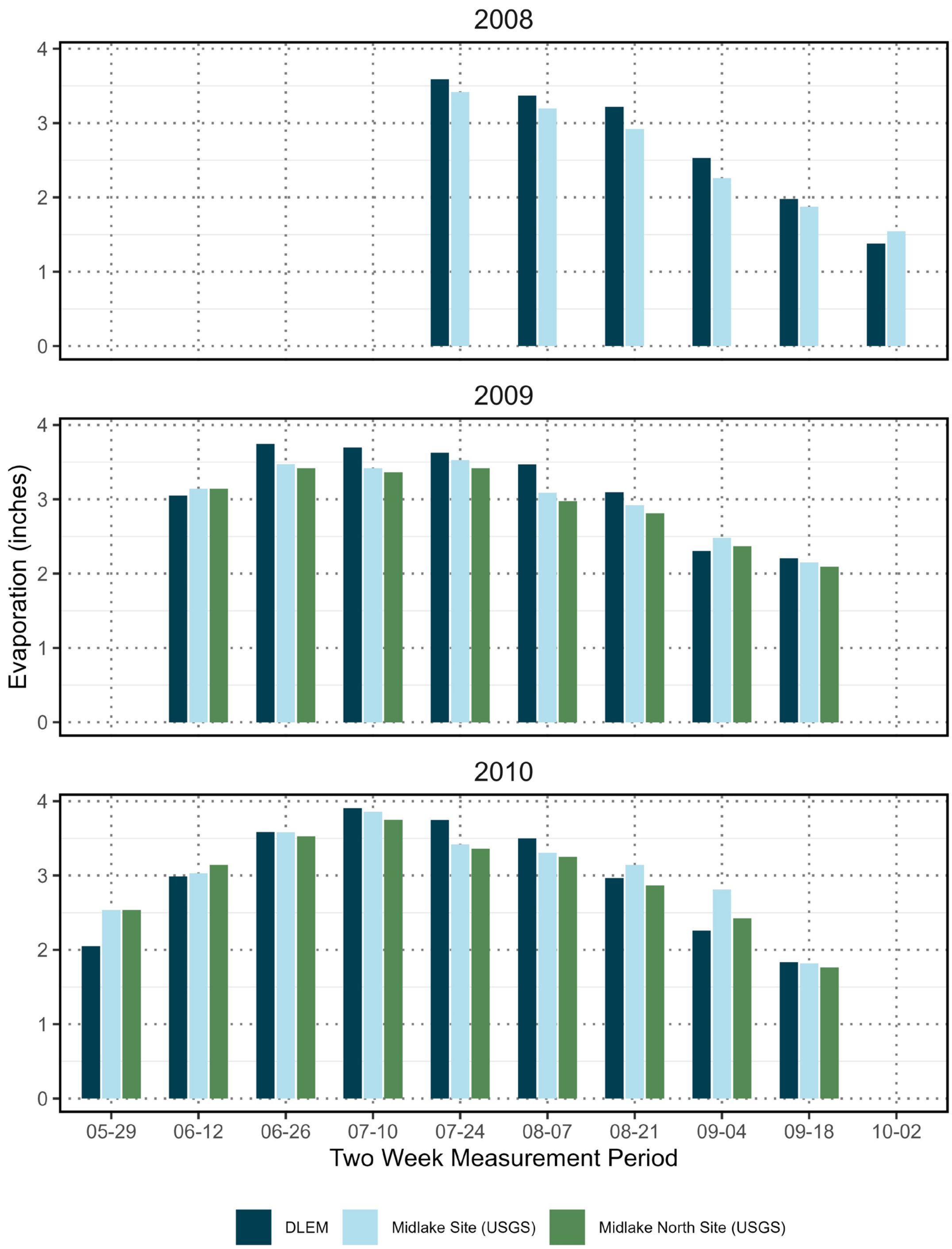



**Figure 12.—Upper Klamath Lake two-week evaporation estimates from the DLEM (dark blue) current conditions runs, and the two field sites reported in Stannard et al. 2013 (light blue and green).**

Another study conducted by Reclamation in 2021 developed open water evaporation estimates from Clear Lake and Gerber Reservoirs using the EC method (Reclamation 2021a). When applied correctly, the EC method is considered one of the most accurate ways to estimate open-water evaporation estimates (Friedrich et al. 2018). The EC method relies on the notion that turbulent water vapor fluxes moving through the air are related to the concentration of water vapor and the speed and frequency of eddies. Through turbulent exchange, energy and mass are transferred between the water surface and the atmosphere by these eddies. EC measurements were collected using shore stations (i.e., land-based) and floating stations (i.e., located over water) at both reservoirs during most months from June to September in 2018 and 2019. Gaps in EC data can occur from power failures, equipment malfunctions, animal disturbances, weather events, and quality control measures (e.g., land contamination from wind direction). These gaps were filled using a method referred to as multiple imputation and can lead to uncertainty in total evaporation estimates.

Monthly evaporation totals from the EC method in Reclamation (2021a) were compared to monthly estimates simulated by the DLEM for both reservoirs. Comparisons were only made when EC measurements were available for the entire month. Figure 13 shows the difference in monthly total evaporation between the DLEM model estimates and the two types of EC estimates. Relative to the EC estimates, DLEM appears to overestimate evaporation in all months except for November with an overall bias of 15.1 and 23.9 percent at Clear Lake and Gerber Reservoirs respectively.

While it is apparent that larger discrepancies exist when comparing field-measured evaporation to modeled evaporation at Clear Lake and Gerber Reservoirs than at UKL, these discrepancies can arise from a variety of reasons. For example, the field study completed by Reclamation to acquire estimates of open-water evaporation from EC methods had a number of complications that led to data gaps that were filled in empirically; however, the number of measurements filled in was never more than 1.25 percent of the total measurements taken for that year and thus does not account for the majority of the difference observed between the two estimation methods. Evaporation is a very difficult parameter to measure, and field measurements using the EC can have anywhere from 15 to 30 percent error for an experienced operator (Allen et al. 2011). Therefore, a percent bias ranging from 2.1 to 23.9 percent depending on the reservoir modeled represents reasonable error for modeled evaporation.

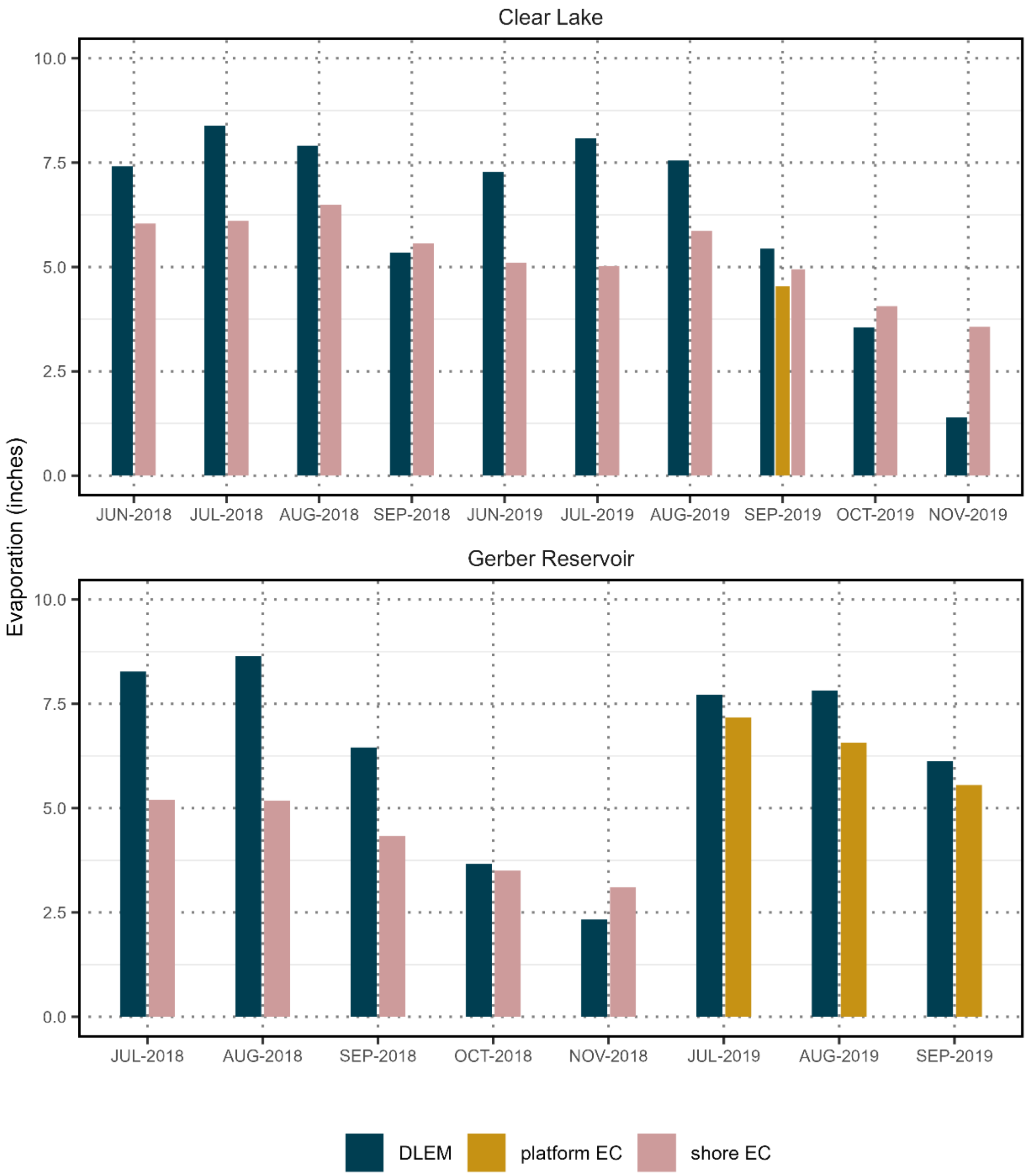



**Figure 13.—Clear Lake and Gerber Reservoir estimates of evaporation from DLEM current conditions runs (dark blue), floating platform eddy covariance (gold), and shore eddy covariance (pink). Eddy covariance estimates originate in Reclamation 2021.**

# 2. Open Water Evaporation Volumes

The annual distribution of average daily evaporation volumes is shown in figure 14 for all modeled waterbodies. Most lakes and reservoirs exhibit a similar distribution of average daily evaporation volumes over the course of the year as the daily evaporation rates (figure 8), with the volume of evaporation peaking in mid to late summer. However, open water evaporation volumes at Lower Klamath NWR follow a very different annual cycle that is representative of the management of the refuge at various parts of the year and the respective surface area of the open water.

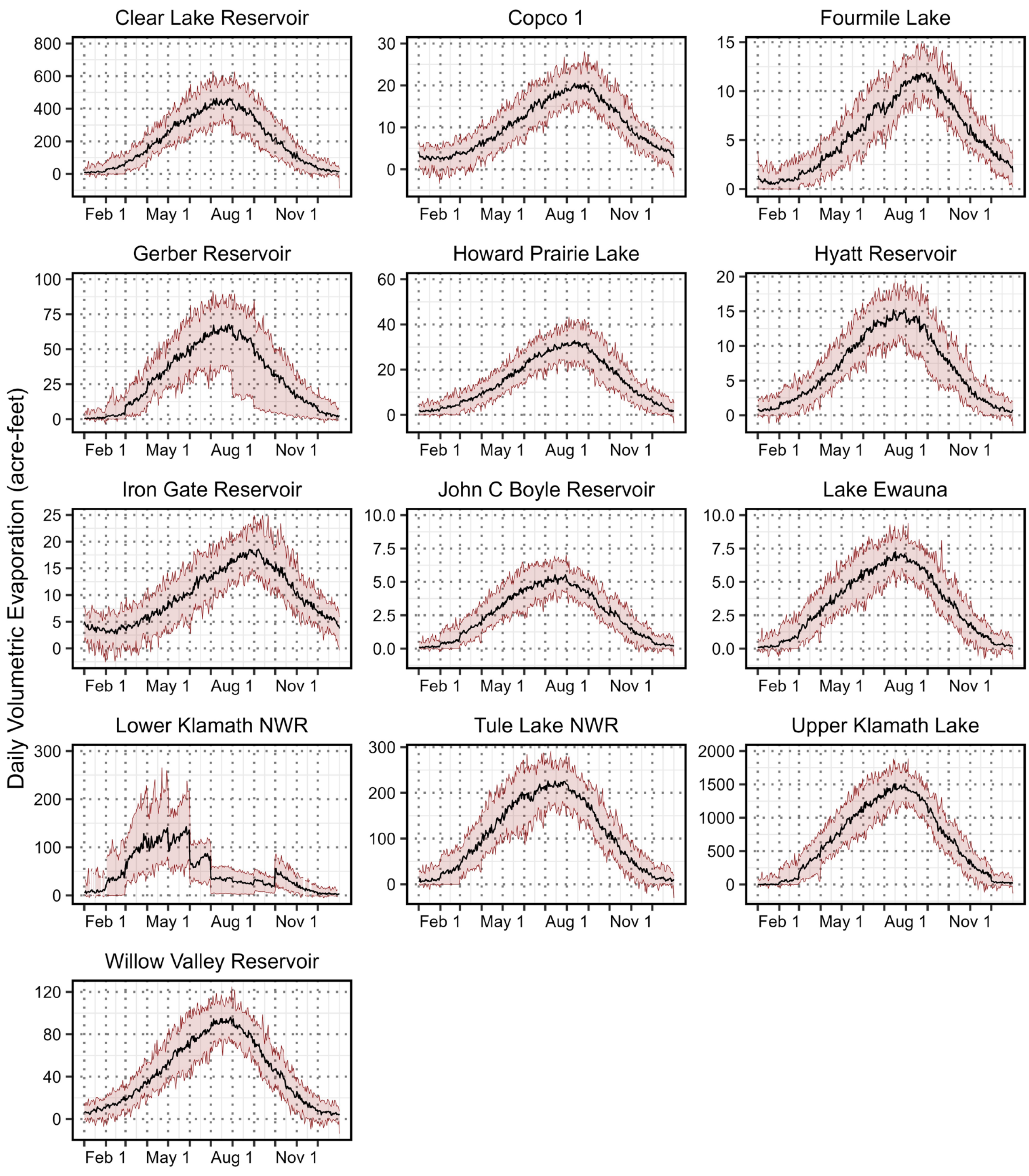



**Figure 14.—Average daily evaporation volumes (acre-ft) from WY 1981 through WY 2020 for the mean/observed depth run under current conditions. Red shading indicates the 5th and 95th percentiles of daily evaporation rates modeled from WY 1981 through WY 2020, while the black line indicates the median value. Note the varying y-axis range among plots.**

Timeseries of annual open water evaporation volumes is shown in figure 15 in addition to the corresponding average annual area for each modeled waterbody. The distribution of annual total open water evaporation volumes is shown in figure 16. While evaporation rates at each of these waterbodies are very similar (figure 8), the volume of water that evaporates from each waterbody varies considerably based on the lake or reservoir size. Upper Klamath Lake, which has a surface area of around 60,000 acres depending on the year, has the largest current conditions volumetric evaporative loss of all modeled waterbodies, ranging from approximately 217 thousand acre-feet (TAF) to upwards of 255 TAF per year. Smaller reservoirs such as Hyatt and Howard Prairie, which are closer to approximately 600 and 1,300 acres in area, have annual volumetric evaporative losses between 2 and 6.5 TAF. There is considerable interannual variability in the volumetric evaporative loss from these reservoirs, due in part to the interannual variability in evaporation rates, but due mostly to the large interannual variability that exists in water body surface areas. For instance, the area associated with Lower Klamath NWR has fluctuated from approximately 1,870 acres in 2015 to over 8,000 acres in previous years.

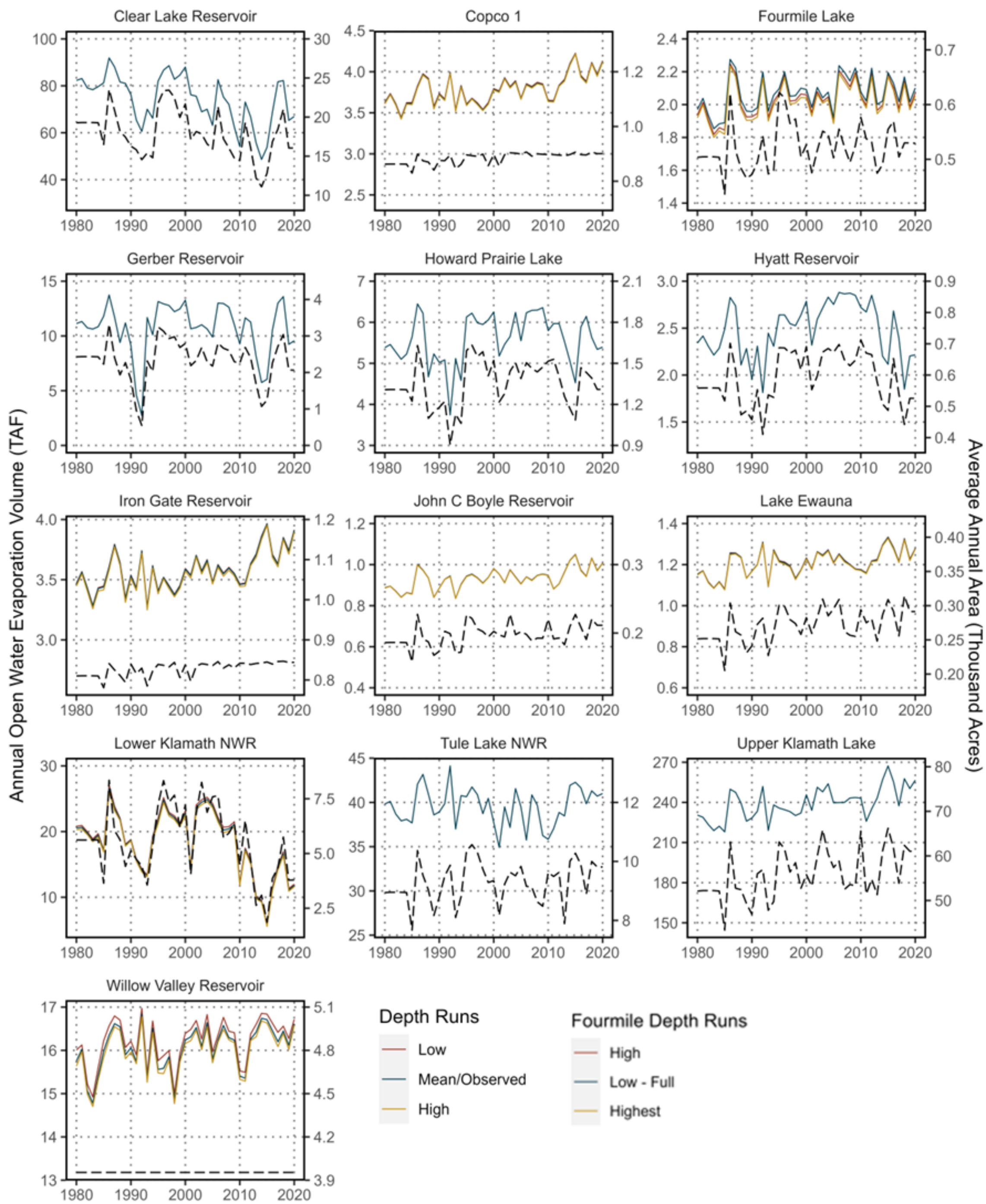



**Figure 15.—Timeseries of annual open water evaporation volume under current conditions in thousand acre-feet (TAF) on left y-axis (where the red, blue, and gold lines indicate the depth of the run) and average annual area (thousand acres; dashed black line) on right y-axis. Note the scale differences on both y-axis for each waterbody.**

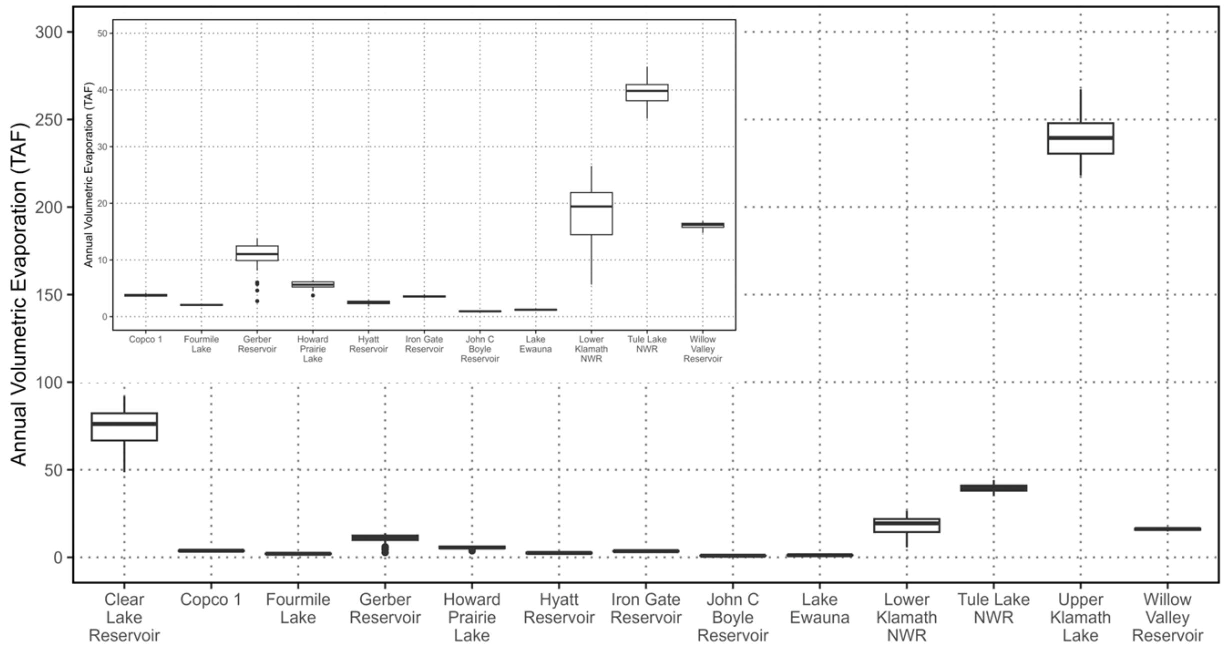



**Figure 16.—Current conditions annual evaporation volumes in thousand acre-feet (TAF) from all modeled Klamath Basin waterbodies for the mean/observed depth run. For clarity, the subset shows annual volumetric evaporation distributions from all waterbodies except Clear Lake Reservoir and Upper Klamath Lake. Note the difference in y-axis scales. The box limits correspond to the 25th and 75th quartiles and the horizontal line within the box represents the median. Whiskers extend to 1.5 ± the interquartile range. Outliers are represented by filled circles.**

## B. Pre-development Conditions

Pre-development simulations performed as part of the Klamath NFS are intended to represent hydrometeorological conditions in the basin between WY 1981 and WY 2020, where development impacts have been removed. By utilizing the same forcing time period (i.e., gridded climate data from WY 1981 and WY 2020), we are able to estimate how the building of reservoirs and dams, the draining of wetlands and shallow open water areas, and agriculture, may have influenced open water evaporation estimates during a recent time period in the UKB. In this section, we present daily, monthly, and annual open water evaporation trends under pre-development conditions.

### 3. Open Water Evaporation Rates

The distribution of pre-development average daily open water evaporation rates at both the high (red line and shading in figure 17) and low water levels (blue line and shading in figure 17) as compared to the current conditions (orange line) median daily evaporation rate is shown in figure 17. The only difference between these three model runs is the average depth of the lake which can be found in table 2 (current conditions) and table 3 (pre-development conditions). As was shown in the current conditions depth uncertainty runs (figure 9), during spring through fall, higher water levels that correspond to a deeper lake are characterized by lower evaporation rates. However, higher water levels can increase evaporation rates in winter due to heat storage effects. This can be seen in figure 17 at Fourmile Lake, where the current conditions median daily evaporation rate (average depth = 45.1 ft) is higher during all warmer months than the pre-development high water level (average depth = 56.4 ft) median daily evaporation rate.

Tule Lake also exhibits seasonal differences in daily evaporation when comparing pre-development high and low water levels and the current conditions water level. Tule Lake is one of the shallower lakes in Upper Klamath Basin, with the observed average depth of Sump 1A fluctuating from between 0 and 18.6 ft, with a median depth of 4.6 ft from WY 1981 through WY 2020. Pre-development average depths are held constant for the duration of each model run and are set at 24.2 ft for the high-water level run and 2.7 ft for the low water level run. In figure 17 it is apparent that the pre-development low water level (blue line and shading) at Tule Lake has higher daily evaporation rates than the pre-development high water level (red line and shading) from early spring through August. However, from September through early January, the pre-development high water level at Tule Lake has higher average daily evaporation rates than the low water level, primarily due to increased heat storage that occurs in deeper lakes. The current conditions average daily evaporation rates at Tule Lake appear to mimic the seasonal dynamics of the pre-development low water level conditions more closely.

Unlike Fourmile and Tule Lake, pre-development average daily evaporation rates at Clear Lake, Lake Ewauna, and Upper Klamath Lake are similar to the current conditions average daily evaporation rates. Lower Klamath Lake, on the other hand, shows pre-development average daily evaporation rates that are slightly lower than the current conditions average evaporation rates from early spring through August. This small change in evaporation rates at Lower Klamath Lake is due to the fact that the lake was deeper in pre-development conditions (average depth ranged from 4.7 to 9.7 ft) than it is currently (mean average depth of 1.9 ft).

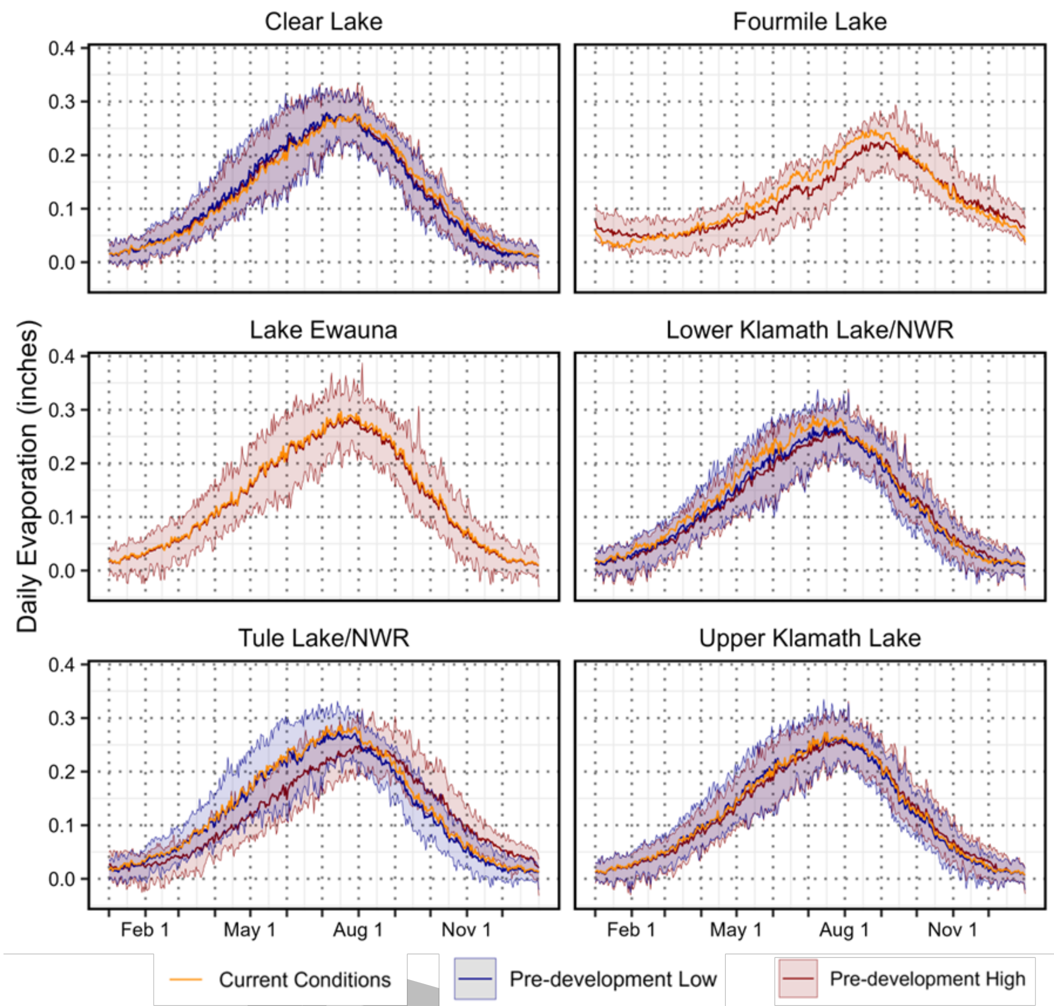



**Figure 17.—Average daily evaporation rates from WY 1981 through WY 2020 under pre-development conditions. Red and blue shading indicates the 5th and 95th percentiles of daily evaporation rates for the pre-development high and pre-development low conditions respectively. The orange line indicates the median evaporation rate for the mean/observed current conditions.**

Similar to average daily evaporation rates, some of the lakes have larger changes than others in annual evaporation rates when comparing current and pre-development conditions (figure 18); however, all lakes have higher median annual evaporation rates under current conditions as compared to pre-development conditions. Tule and Lower Klamath Lake have the largest differences in median annual evaporation when comparing pre-development and current conditions. Both lakes exhibit higher median annual evaporation rates during current conditions than they do during pre-development conditions, with the largest median difference of approximately 0.42 ft at LKL and 0.35 ft at Tule Lake. Median differences in annual evaporation rates at Fourmile are about half that seen at Tule and LKL at approximately 0.22 ft, while median differences at Lake Ewauna, Clear Lake, and UKL are even smaller at approximately 0.15, 0.04, and 0.7 ft, respectively.

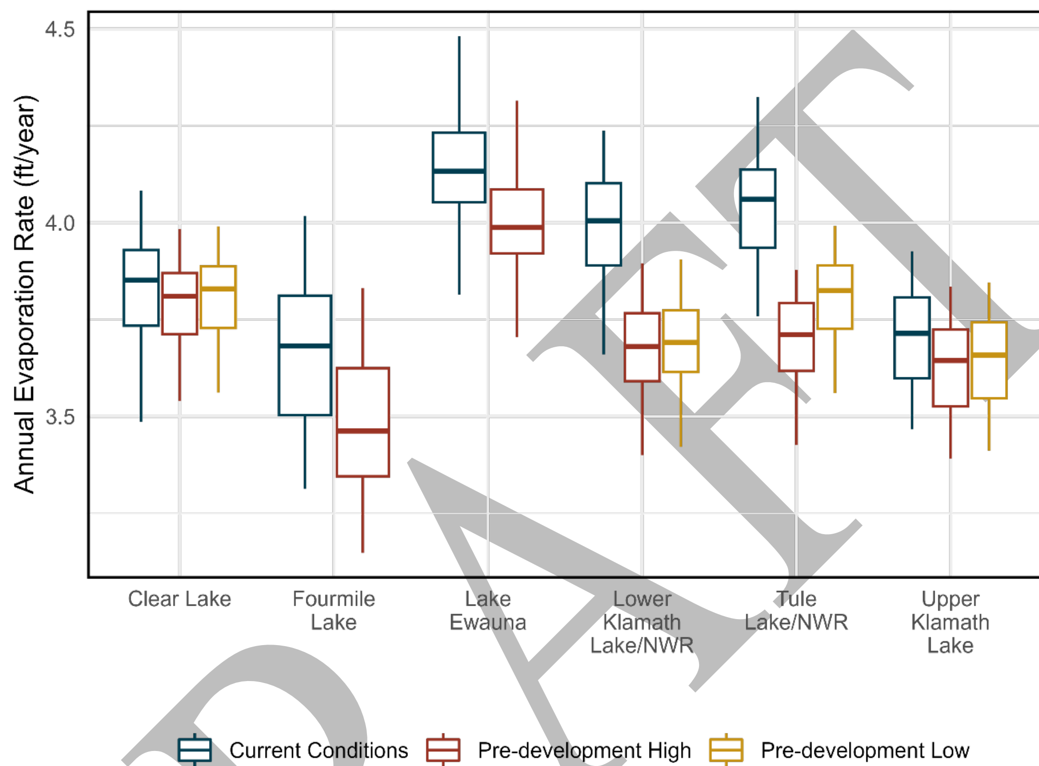



**Figure 18.—The distribution of pre-development high (red), pre-development low (gold), and current conditions mean/observed (dark blue) annual open water evaporation rates from WY 1981 through WY 2020. The box limits correspond to the 25th and 75th quartiles and the horizontal line within the box represents the median. Whiskers extend to 1.5 ± the interquartile range. Outliers are represented by black filled circles.**



# 4. Open Water Evaporation Volumes

Pre-development open water evaporation volumes are estimated from daily evaporation rates multiplied by the surface area of the lake at both high and low water levels if data was available. The average annual surface area of each lake under high and low water level pre-development conditions can be seen in figure 19. Observed average annual areas from WY 1981 through WY 2020 are also shown in figure 19. The largest differences in surface areas when comparing pre-development and current conditions occurs at Lower Klamath and Tule Lakes. Drainage of these lakes and surrounding areas reduced inflows significantly thus decreasing their average annual areas by approximately 80 and 93 percent, respectively, from pre-development high water level conditions. In contrast, pre-development and current conditions surface areas at Clear Lake and Fourmile Lake are fairly similar, while pre-development surface areas at UKL and Lake Ewauna are slightly larger than current conditions.

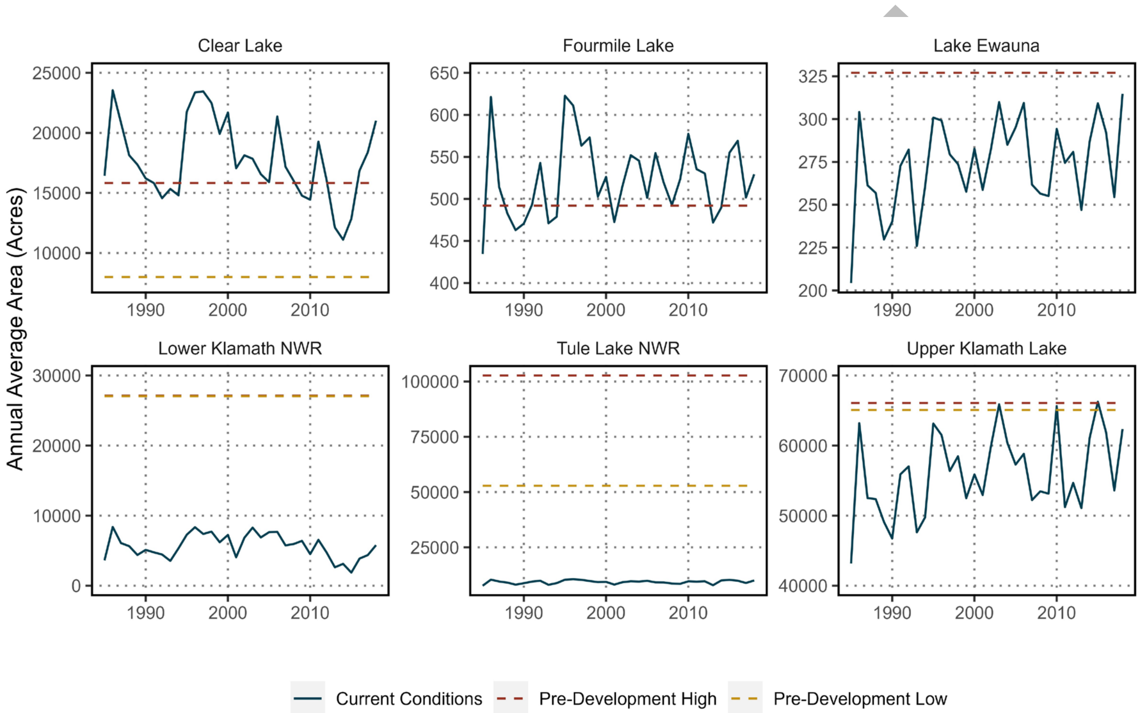



**Figure 19.—A timeseries of current conditions (dark blue solid line) average annual area compared to the fixed high (red dashed line) and fixed low (gold dashed line) pre-development areas.**

The largest volume of open water evaporation during pre-development conditions occurs at Tule Lake, assuming high water levels with over 380,000 acre-ft of evaporation occurring annually. This volumetric loss is over eight times the volume of average annual evaporation that occurs under current conditions (figure 20). UKL has the second largest contribution to open water evaporation volume under pre-development conditions with approximately 240,000 acre-feet loss annually; however, that annual quantity (ie. volume) of evaporation has not significantly changed from current conditions.

Lower Klamath Lake used to cover approximately 27,000 acres in pre-development conditions (excluding overflow from Lake Ewauna during spring runoff) but in current conditions rarely is larger than 8,000 acres. This leads to a five-fold increase in the open water evaporation volume when comparing current conditions to pre-development conditions.

Lake Ewauna was also larger in area during pre-development conditions than it is now; however, this increase in area is less than 100 acres. Evaporative volumes from Lake Ewauna are small in comparison to the other natural lakes due to its small size with an annual median of around 1.2 TAF in current conditions and 1.3 TAF in pre-development conditions.

Pre-development evaporation volumes from Fourmile Lake are less than current evaporation volumes after the enlargement of the lake due to the construction of Fourmile dam. Pre-development evaporation volumes from the natural lake were around 1.7 TAF while current evaporation is around 2.1 TAF. Similarly, the average surface area of Clear Lake is larger during current conditions than it was pre-development. Current evaporation volumes from Clear Lake are approximately 77 TAF, while pre-development evaporative volumes are closer to 60 TAF.

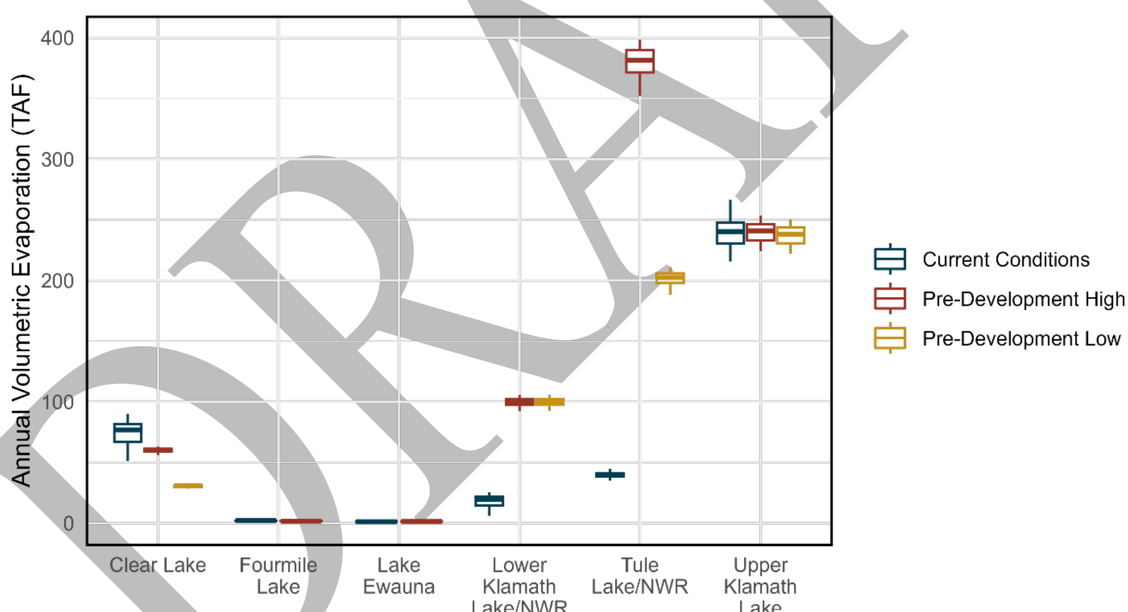



**Figure 20.—The distribution of pre-development high (red), pre-development low (gold), and current conditions mean/observed run (dark blue) annual evaporation volumes in thousand acre-feet (TAF) from WY 1981 through WY 2020. The box limits correspond to the 25th and 75th quartiles and the horizontal line within the box represents the median. Whiskers extend to 1.5 ± the interquartile range. Outliers are represented by filled circles.**

# IV. Model Sensitivity

Changes in the magnitude of different parameters and data inputs to a model can influence results to varying degrees. The sensitivity of a model to different parameters or inputs can be useful in understanding a model's degree of uncertainty (which is discussed in the next section). We investigate three different areas of uncertainty in our DLEM modeling and document how sensitive daily, monthly, and annual evaporation rates are to each area. The three areas of uncertainty are fetch length, forcing data, and wind speed, described as:

1. The fact that fetch length is estimated from one lake mask, despite the fact that surface area changes over time as lake depth changes.
2. The use of spatially-averaged climate data over each lake mask as opposed to obtaining climate data from one central gridcell.
3. The ability of gridded climate datasets to capture wind dynamics given the spatial and temporal variability of wind on a daily timestep.

In the DLEM, fetch is estimated from a constant lake surface area and does not take into account how the surface area of a lake can change over time as lake levels change. To better understand how sensitive evaporation rates are to changes in fetch length, Fourmile Lake and Clear Lake Reservoir are used as test cases. Fetch is estimated for both reservoirs at an area 10 percent greater than the average area used in all current condition model runs (called the 'High' run) and 10 percent less than that average area (called the 'Low' run).

Figure 21 shows the distribution of differences in average daily evaporation rates between the High and Low fetch sensitivity runs for both Fourmile Lake and Clear Lake Reservoir. The DLEM model appears minimally sensitive to changes in fetch, with the maximum median difference in daily evaporation rates between Low and High fetch runs equaling 0.0005 in (0.46 percent median difference in evaporation rate) for Fourmile Lake and 0.0003 in (0.43 percent median difference in evaporation rate) for Clear Lake Reservoir. The larger differences in evaporation rates at Fourmile Lake occur during the winter months on abnormally windy days. Despite larger differences in the winter average daily evaporation rates between the low and high fetch runs, differences in annual evaporation rates are negligible (figure 22). The median WY (ie., annual) evaporation difference between the low and high fetch sensitivity runs are 0.0047 and 0.0058 in for Clear Lake Reservoir and Fourmile Lake respectively. Overall, this fetch sensitivity analysis shows that the assumption to use a constant surface area despite fluctuating water levels has minimal impact on modeled daily evaporation rates.

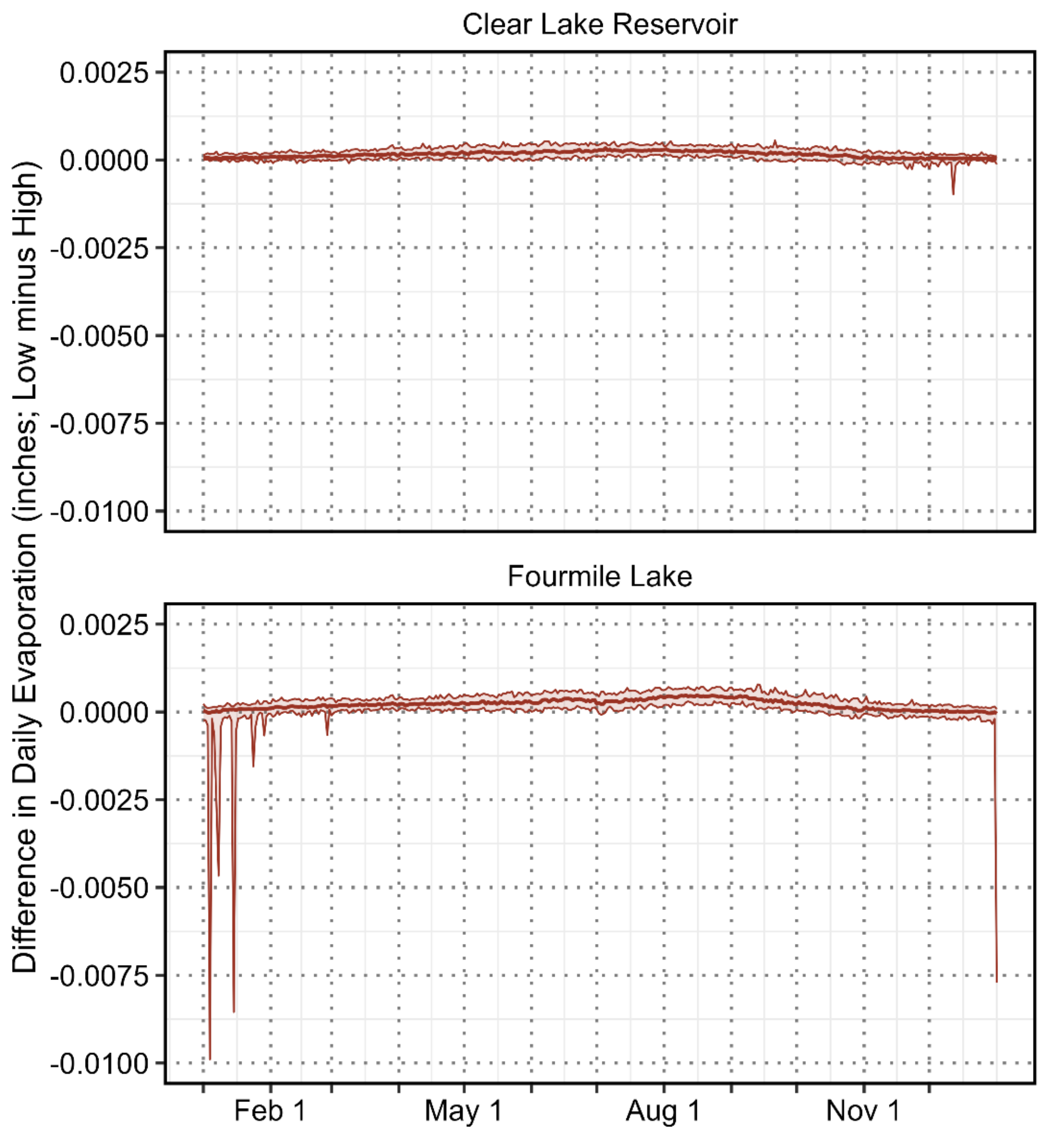



**Figure 21.—Average difference in average daily open water evaporation rates from WY 1981 through WY 2020 between model runs where fetch is estimated at 10 percent less surface area than average minus the run where fetch is estimated at 10 percent more surface area than average. Median differences are shown with the thick dark red line, while the 5th and 95th percentile differences are outlined by the thin dark red line. Differences are computed as the ‘Low’ run minus the ‘High’ run.**

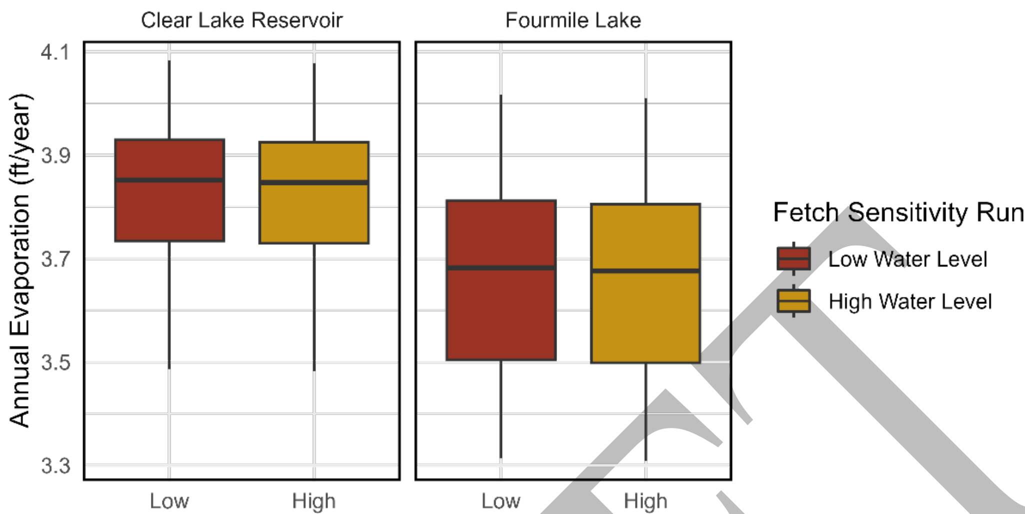



**Figure 22.—The distribution of WY open water evaporation rates from WY 1981 to WY 2020 the low water level (red) and high-water level (gold) fetch sensitivity runs at Clear Lake Reservoir and Fourmile Lake. The box limits correspond to the 25th and 75th quartiles and the horizontal line within the box represents the median. Whiskers extend to 1.5 ± the interquartile range. Outliers are represented by black filled circles.**

Another input that DLEM results could be sensitive to comes from the assumption that area-averaged climate data is the best way to represent climate across large reservoirs, given DLEM is a one-dimensional model and provides reservoir-average estimates of evaporation. To investigate this assumption, Upper Klamath Lake is used as a test lake as it is the largest modeled lake in the Upper Klamath Basin and is over 25 miles long. DLEM runs are completed using climate data acquired from a single gridMET gridcell at four different locations across UKL (figure A-3) and compared to the area-averaged climate data UKL run (using the ‘UKL w/o Caledonia, Tulana, or Goose Bay’ configuration). Figure 23 shows the distribution of mean differences in daily evaporation rates between the area-averaged climate data run at UKL and the single gridcell climate data runs (for each combination). Differences in daily evaporation rates are minimal with median differences at the north locations (Agency and North UKL) being slightly less than the area-averaged UKL run while median differences at the more southern UKL locations (Mid and South UKL) are slightly larger than the area-averaged UKL run. Differences are more pronounced in the summer months, where daily evaporation is at most ± 0.02 in different from the area-averaged UKL run. Given daily evaporation rates range from approximately 0.2 to 0.3 in/day in the summer depending on the day and the location, it appears that using spatially-averaged climate data instead of a single gridcell impacts daily evaporation rates by upwards of 10 percent in the summer.

Annual differences in evaporation between the area-averaged and single gridcell UKL runs are shown in figure 24. The more southernly locations have slightly more evaporation due to increased temperatures than the more northernly locations, with the area-averaged run annual evaporation falling in-between. Median differences in annual evaporation rates between runs are minimal though, with 3.78 ft of evaporation at South UKL as compared to 3.69 ft of annual evaporation at Agency and 3.72 ft of evaporation for the area-averaged UKL run.

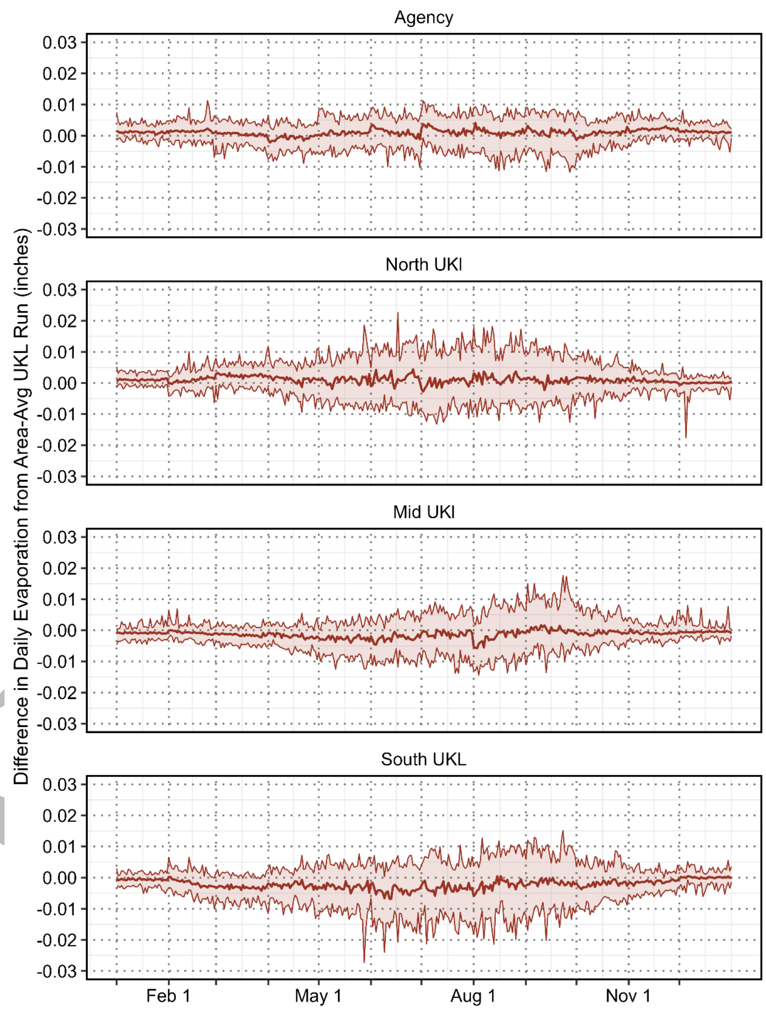



**Figure 23.–Average difference in average daily open water evaporation rates from WY 1981 through WY 2020 between the standard 'UKL w/o Caledonia, Tulana, or Goose Bay' run with area-averaged climate data and the single gridcell climate data runs at various locations across UKL. Median differences are shown with the thick dark red line, while the 5th and 95th percentile differences are outlined by the thin dark red line. Differences are computed as the standard run minus the single gridcell run.**

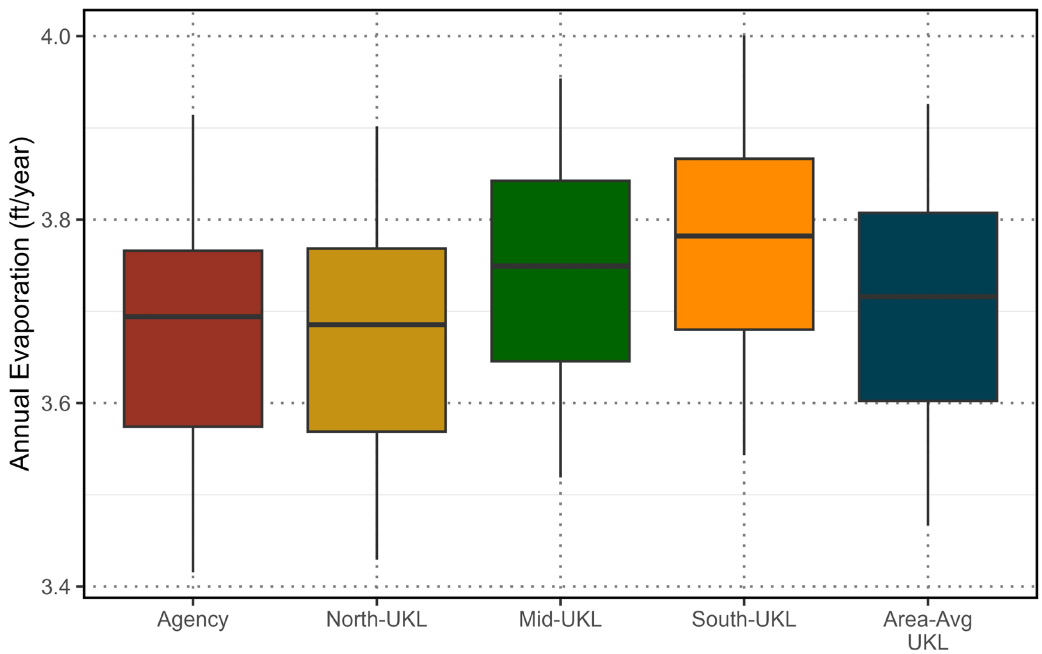



**Figure 24.—Annual evaporation rates from WY 1981 through WY 2020 for the four single gridcell UKL runs and the area-averaged climate data UKL run (Area-Avg UKL). The box limits correspond to the 25th and 75th quartiles and the horizontal line within the box represents the median. Whiskers extend to 1.5 ± the interquartile range. Outliers are represented by black filled circles.**



We also investigate the sensitivity of DLEM to wind speed, given its spatial variability across small distances and the uncertainty associated with wind speed in gridded datasets. Local topography and surface roughness have been shown to significantly impact wind speed thus making it more difficult to interpolate wind speed fields as compared to other climate variables (Wieringa 1986). gridMET interpolated wind speeds are found to have positive biases across forested areas, with higher correlations between observed wind speed and the gridMET interpolated wind speeds in open areas (Abatzoglou 2013). Correlations between gridMET gridded windspeed and observations is around 0.68 for the cold season and 0.62 for the warm season with positive biases of 5 to 30 percent depending on location (Abatzoglou 2013). The sensitivity of other climate variables is not investigated as variables such as maximum and minimum temperatures are more easily represented in gridded climate datasets. For instance, the correlation of gridMET maximum temperatures to observations is upwards of 0.94 to 0.95 (Abatzoglou 2013).

The sensitivity of DLEM to wind speed is investigated using a series of sensitivity runs. Specifically, wind speed sensitivity runs are completed by increasing and decreasing daily wind speeds by 20 percent from the current conditions at Fourmile Lake, Clear Lake Reservoir, and Upper Klamath Lake. Wind sensitivity runs at UKL are run using the ‘UKL w/o Caledonia, Tulana, or Goose Bay' lake configuration. At UKL, wind can heavily influence lake dynamics as water surface elevation can vary spatially across the lake on windy days which is why the USGS uses four separate gages to measure water surface elevation (ORWD 2021). In contrast, Fourmile Lake is a much smaller lake where wind is likely less spatially heterogeneous across the lake surface. Clear Lake Reservoir is a larger lake like UKL; however, it is situated in a sunnier, warmer area than UKL.

Figure 25 shows the difference in average daily evaporation rates between the current conditions run and the two wind sensitivity runs where wind was increased and decreased by 20 percent at Clear Lake Reservoir, Fourmile Lake, and Upper Klamath Lake. In all seasons except winter, increasing wind speed increases daily evaporation by upwards of 0.015 in/day, which is less than 5 percent of the maximum daily evaporation rate. Decreasing wind speed by 20 percent has a similar decrease in evaporation rates with decreases not more than 0.015 in/day. Interestingly, in the winter months, this phenomenon is reversed at Fourmile Lake; increasing daily wind speed in winter months decreases daily evaporation rates while decreasing daily wind speed in winter months increases evaporation rates.

This winter trend where increasing wind speed decreases evaporation rates is also apparent at the monthly timescale at Fourmile Lake, where mean monthly evaporation rates among the wind speed test simulations are shown in figure 26. This phenomena occurs due to the Penman Combination equation that DLEM uses (Zhao, G. 2019; equation 1 above) to estimate evaporation where the radiative and turbulent fluxes are separated. Increasing wind speed throughout the summer increases evaporation which in turn reduces the amount of heat storage (ie. water temperatures; see figure A-3) available to fuel evaporation in the winter. In addition, in winter the turbulent component of the evaporation equation which increases when wind speed increases, is much smaller than in summer as the vapor pressure deficit is small in winter. These two phenomena can lead to less evaporation in winter from increased wind speed depending on the heat storage capacity of the lake.

Given UKL and Clear Lake Reservoir are not as deep as Fourmile Lake, the finding that increasing wind speed decreases evaporation in winter months rarely occurs due to smaller heat storage effects. In figure 25, it is shown that only during late November and December does increasing wind speed decrease evaporation rates at both Clear Lake Reservoir and UKL. Otherwise, throughout the remainder of the year, increasing wind speed increases evaporation. Despite the different daily sensitivities to wind speed during the winter months, at the annual scale all waterbodies show the same sensitivity to wind speed, where increasing wind speed increases annual evaporation rates. These annual evaporation rates are displayed in figure 27 where the annual median increases by 3.4, 3.7, and 3.5 percent for the plus 20 percent wind runs at Clear Lake Reservoir, Fourmile Lake, and UKL, respectively. In contrast, annual medians decrease by approximately -3.5, -3.8, and -3.5 percent for the minus 20 percent wind runs at Clear Lake Reservoir, Fourmile Lake, and UKL, respectively.

While it appears that the DLEM model does have some sensitivity to how gridded climate data is applied and the uncertainty surrounding interpolated wind fields within gridded datasets, the sensitivities are all less than 10 percent at daily timescales. It has been shown that error associated with observational evapotranspiration measurements can be upwards of 30 percent (Allen et al. 2011) and measuring open water evaporation is even more difficult. Therefore, model sensitivities of less than 10 percent are reasonable and acceptable as long as the modeler and end users are aware of the different sensitivities and their magnitudes.

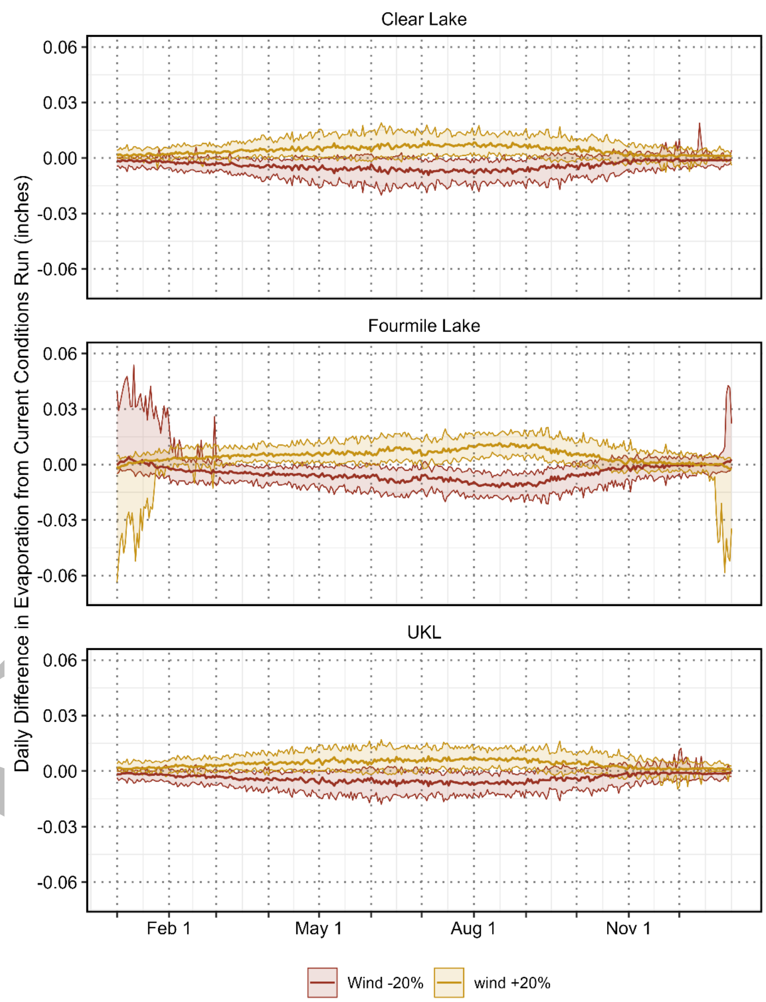
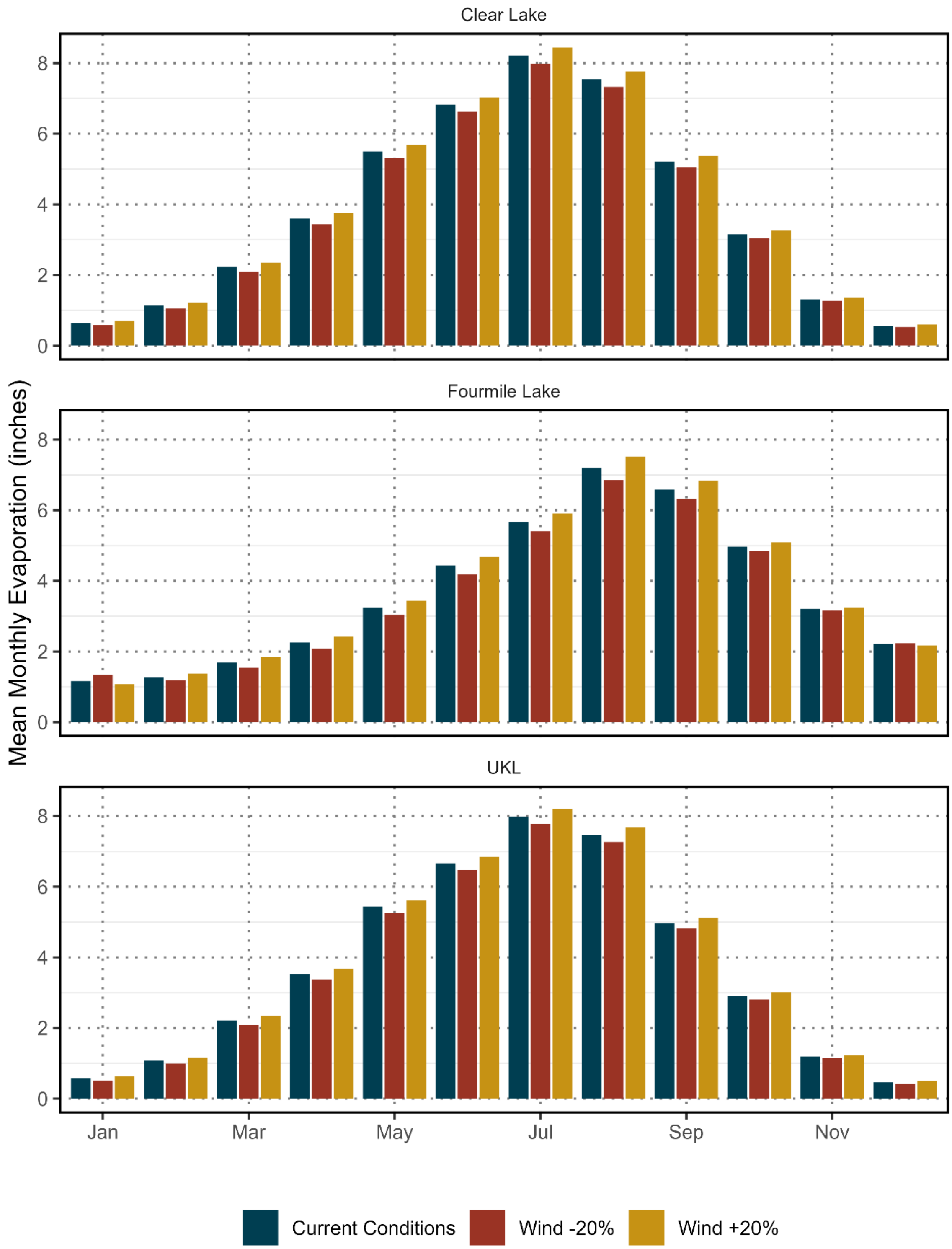
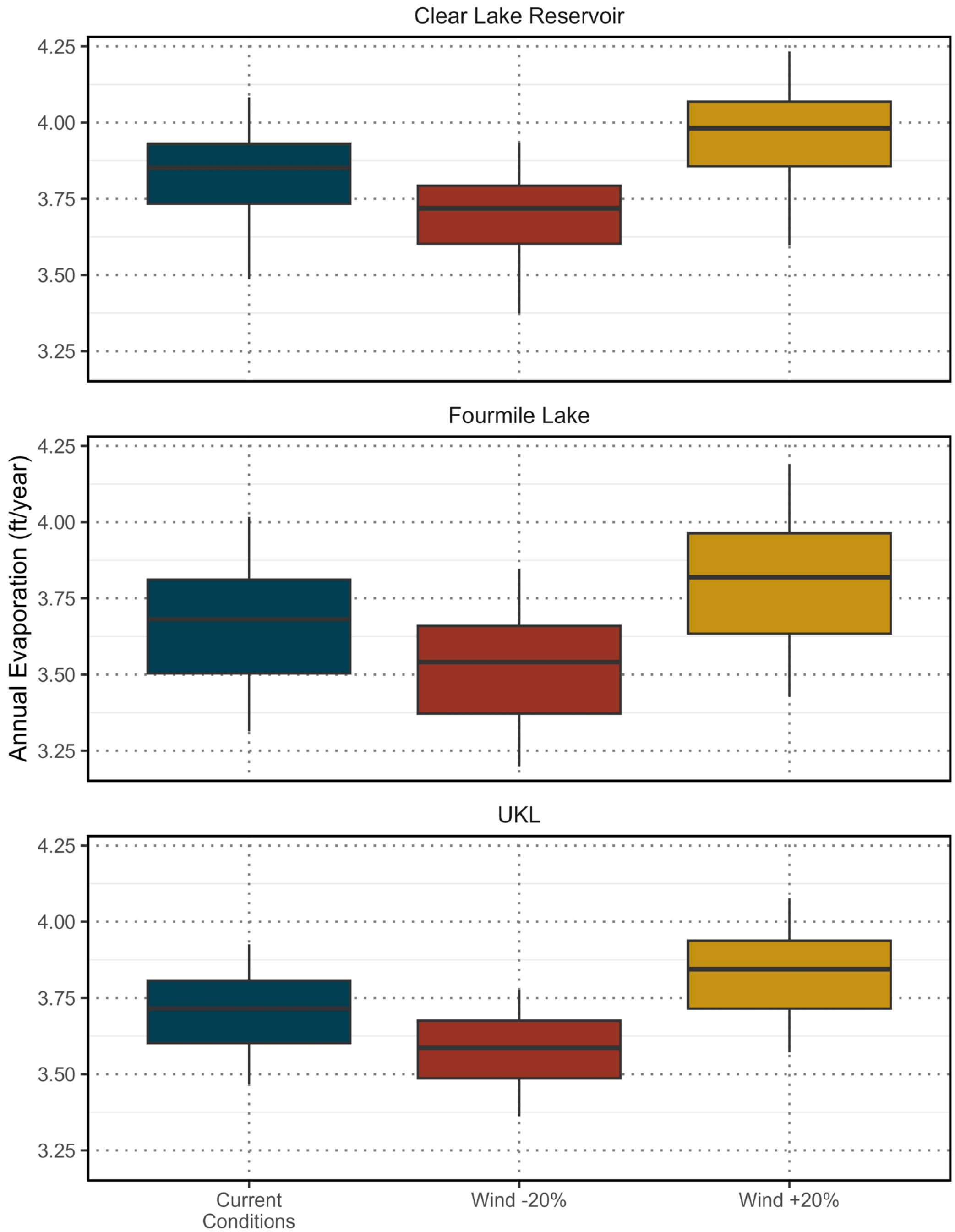



**Figure 25.—The distribution of differences in daily evaporation amounts from the mean/observed current conditions run and each wind sensitivity run from WY 1981 through WY 2020. Median differences are shown with the thick blue (plus 20 percent wind) and red (minus 20 percent wind) line, while the 5th and 95th percentile differences are outlined by the thinner colored line of each respective run. Differences are computed as the wind ± 20 percent run minus the standard run.**




1217 **Figure 26.—Mean monthly evaporation for each wind sensitivity run at UKL, Fourmile Lake, and**
1218 **Clear Lake Reservoir from WY 1981 through WY 2020.**




1219 **Figure 27.—Annual evaporation rates from WY 1981 through WY 2020 for each wind**
1220 **sensitivity run at Clear Lake Reservoir, Fourmile Lake, and UKL. The box limits**
1221 **correspond to the 25th and 75th quartiles and the horizontal line within the box**
1222 **represents the median. Whiskers extend to 1.5 ± the interquartile range. Outliers are**
1223 **represented by black filled circles.**

# V. Model Uncertainty

All hydrologic models have a level of uncertainty associated with model results. Uncertainty analyses help identify a range of plausible outcomes which add important context and information to the model results. There are two types of uncertainty: (1) aleatory uncertainty, or uncertainty that will always exist from the inherent randomness in natural processes, and (2) epistemic uncertainty, or uncertainty that is not constant and can be reduced through improved understanding of these physical processes or the data that represents them. As hydrologic models and the data used in these models advance, epistemic uncertainty is reduced; however, aleatory uncertainty will always be present. Model uncertainty is different from model sensitivity that is investigated in the above section. As was quoted by the United States Environmental Protection Agency, sensitivity analyses are ‘the principal evaluation tool for characterizing the most and least important sources of uncertainty in environmental models’ (EPA 2009). All of the investigated model sensitivities combine to help the end user understand part of the quantitative level of uncertainty associated with the DLEM estimates of evaporation rates. Below, we will discuss two other areas of uncertainty that can impact how results are interpreted. These two areas of uncertainty are related to the choice of reservoir evaporation model and the choice of meteorological forcing dataset.

## A. Model Choice Uncertainty

There are multiple ways that open water evaporation has been modeled. The choice of model and how that model parameterizes the relevant equations to calculate open water evaporation lends to model structure uncertainty. While it is not within the scope of this project to review all methods or models that provide open water evaporation rates, this section will highlight three different models of varying complexity that could be used to estimate open-water evaporation: (1) an iterative energy balance and vapor transfer model, (2) a bulk-aerodynamic method, and (3) a one-dimensional lake model coupled to a numerical weather prediction model.

DLEM is an open water evaporation model that utilizes both energy budget and mass transfer components to simulate open water evaporation on a daily timestep. While DLEM does simulate the major physical processes that impact open water evaporation, DLEM does not explicitly model advective heat flux, which for some lakes and reservoirs is a significant part of their heat balance (Friedrich et al. 2018; Reclamation 2015). Advective heat flux is a very difficult component to model due to the difficulty in accurately measuring the temperature of all flows into and out of the reservoir. In addition, although DLEM does simulate negative evaporation that occurs when condensation forms during cold, wet winters, DLEM does not specifically represent ice formation or sublimation that might occur on the surface of the lake.

The parameterization of certain terms within the DLEM model framework is another source of uncertainty. The accuracy of reservoir area and depth data could influence evaporation estimates. The accuracy of reservoir area affects the fetch length and the wind function, while the depth of the reservoir directly impacts heat storage. Area is held constant when estimating fetch for each reservoir and could lead to uncertainty in the model results if the reservoir's area fluctuates greatly. Results from the fetch sensitivity analysis above confirm that evaporation rates are minimally sensitive to changes in reservoir area and thus fetch, and therefore the assumption to use a constant surface area in the DLEM does not significantly impact evaporation rates. Some of the modeled waterbodies have limited depth observations and thus constant depth values are used for the entire simulation. To this end, model runs are completed using the plausible range in depths for each reservoir and results suggest that the DLEM model is more sensitive to changes in depth than it is to changes in surface area.

To further explore model choice uncertainty, simulated open water evaporation rates are compared between DLEM and another energy balance model that simulates vapor transfer and heat storage. The Complementary Relationship Lake Evaporation (CRLE) model (Morton 1985, 1983, 1979) is commonly used to estimate reservoir evaporation for water management on a monthly timestep. The CRLE model iteratively solves energy balance and vapor transfer equations to estimate ambient potential evaporation which is further used to determine the equilibrium wet surface temperature. The equilibrium wet surface temperature is then used to calculate the slope of the saturation vapor pressure curve used in a modified Priestly-Taylor equation that calculates open water evaporation. However, CRLE does not model the effects of wind or fetch on lake evaporation. CRLE relies on a constant average depth and does not consider temporal variations in water surface elevation. This can lead to uncertainty in evaporation estimates for reservoirs with monthly or sub-monthly fluctuations in depth. For the CRLE comparison runs, CRLE is run from 1979 through 2020 with results focusing on WY 1981 through WY 2020. CRLE is forced with the same spatially averaged gridMET climate data and run with the constant mean depths shown in table 2.

Figure 28 shows a comparison of monthly average evaporation at each modeled reservoir using both DLEM and CRLE. It is apparent that DLEM estimates higher rates of evaporation in the spring and summer months than CRLE and in most cases CRLE estimates higher fall evaporation rates. By focusing in on the reservoirs that were modeled with constant depth for both DLEM and CRLE runs (Copco 1, Fourmile Lake, Iron Gate Reservoir, JC Boyle Reservoir, Lake Ewauna, and Lower Klamath NWR) it is likely that monthly differences in evaporation rates are a product of varying formulations of reservoir heat storage. Other model differences related to forcing variables (e.g., wind speed) may play a role. While the CRLE model is a great tool for quick evaporation estimates at a monthly timestep, it is insensitive to differences in temperature, humidity, and wind speed that occur from land onto water and DLEM likely does a better job at representing monthly trends in open water evaporation.

The increased spring and summer evaporation in DLEM leads to higher annual evaporation rates, relative to CRLE, at all modeled reservoirs (figure 29). The differences in median annual evaporation rates ranges from approximately 0.05 ft (0.6 in) at Upper Klamath Lake to 0.55 ft (6.6 in) at JC Boyle Reservoir and represent 1.3 and 12.7 percent of the annual evaporation rates respectively. The average annual median difference among all lakes and reservoirs when comparing DLEM to CRLE is approximately 6.9 percent. Given these small annual differences, either the DLEM or CRLE model is likely sufficient at an annual timescale.

In addition to using an energy and heat balance model like DLEM or CRLE to estimate open water evaporation, another option is to use a bulk-aerodynamic method which is based on Fick's first law of diffusion. Fick's first law of diffusion states that the diffusion of heat and water vapor occurs from areas of high concentration to areas of low concentration at a rate that is proportional to the spatial gradient of heat or water vapor. This method of estimating evaporation is relatively simple as it only relies on meteorological measurements of wind speed, air temperature, relative humidity, and water surface temperature. This method has some limitations as at smaller timescales such as hourly or daily, it may be necessary to account for the effects of atmospheric stability on the mass transfer coefficients (Finch and Hall 2001). Another shortfall of the bulk-aerodynamic method is that there are coefficients within the equations used that require calibration, selection of a fixed coefficient, or more advanced solving techniques (Reclamation 2022b). This method is also very sensitive to errors in the vapor pressure gradient (Finch and Hall 2001). All of these limitations lead to uncertainty in the model results when using a bulk-aerodynamic method to estimate open water evaporation.

One of the more computationally expensive but more physically-based ways to model open water evaporation is to use a lake model coupled to a numerical weather prediction model which allows for feedback between open water surfaces and the lower atmosphere (Stepanenko et al. 2015). One-dimensional (1-D) lake models range from one-layer bulk models to finite-difference models with k-ε turbulence closures, where water temperature can be simulated at multiple depths in the water column. Modeled temperature depth profiles can be coupled to numerical weather prediction models that can expand evaporation results two-dimensionally and identify spatial patterns in surface evaporation rates across large reservoirs or lakes. Limitations with this method of estimating evaporation can stem from the vertical discretization scheme of the 1-D lake model not sufficiently capturing thermal stratification and layering in deep lakes (Wang et al. 2019). Parameterizing diffusivity can also lead to uncertainty in model results as wind-driven eddy diffusivity is hard to parameterize in deep lakes and should be tuned appropriately based on lake depth. Radiation dynamics can also be difficult to simulate in lakes that undergo biological processes that influence optical processes (e.g., algal growth) which may lead to increased uncertainty in model results in lakes with high biological activity.

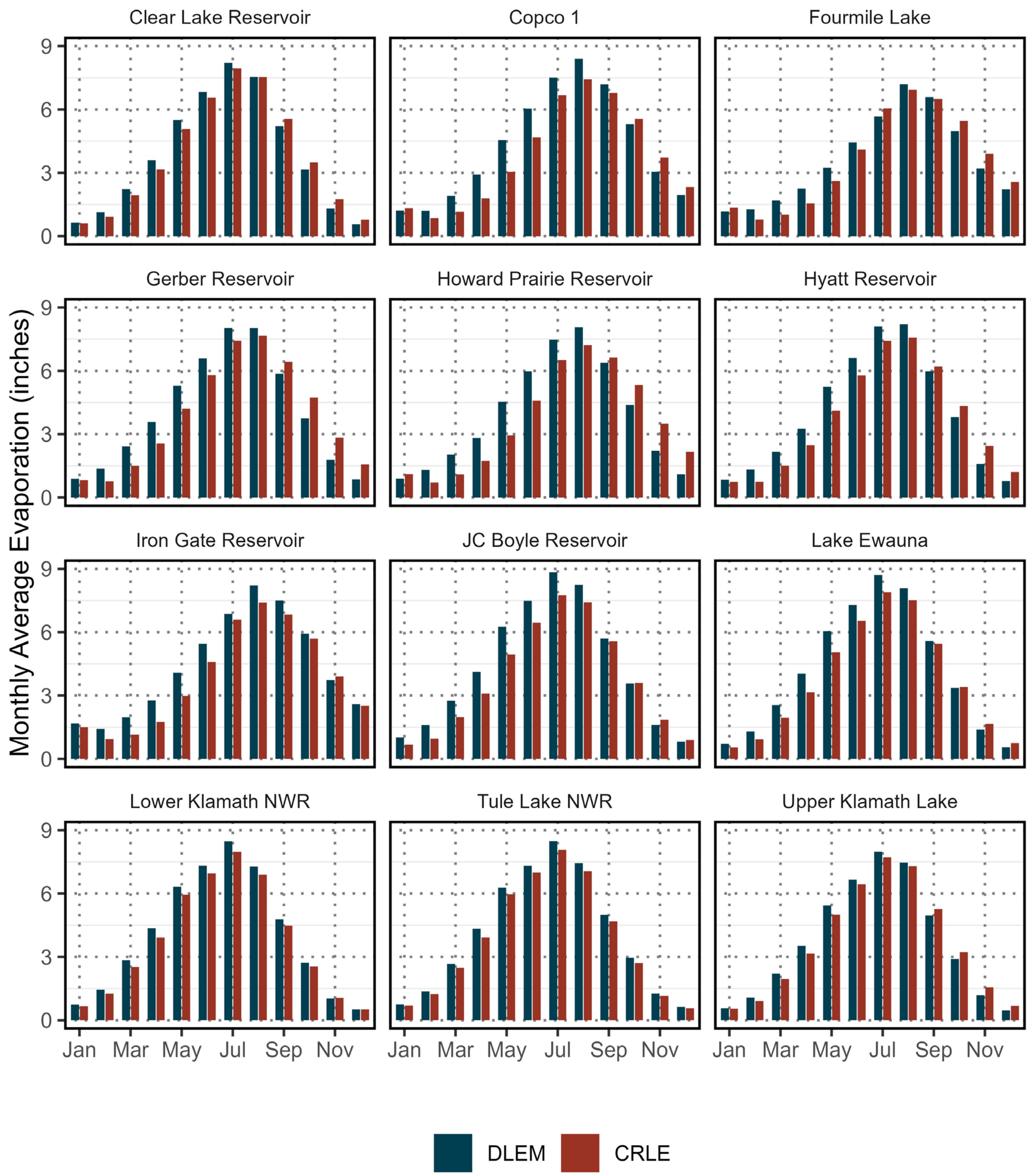



**Figure 28.—Monthly average evaporation rates at each waterbody using the DLEM (blue) and CRLE (red) models from WY 1981 through WY 2020 under current conditions.**

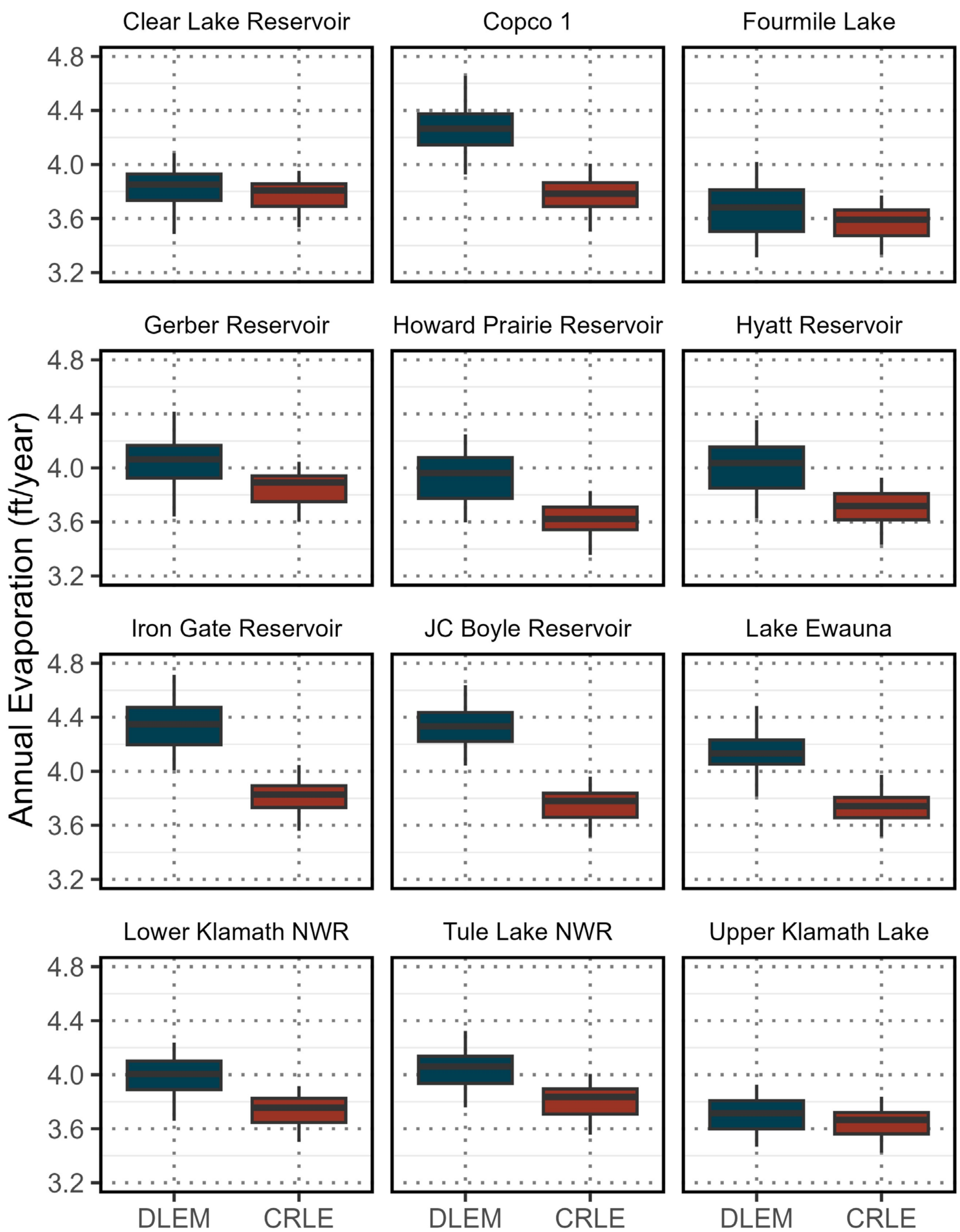



**Figure 29.—The distribution of annual evaporation for each wateryear between WY 1981 and WY 2020 under current conditions. The DLEM model is in dark blue and the CRLE model is in red.**

## B. Climate Dataset Uncertainty

Uncertainty in simulated open water evaporation estimates can also stem from the choice of climate forcing dataset. For instance, one global lake evaporation dataset acknowledges this uncertainty and thus forces their open water evaporation model with the average value of three different gridded reanalysis datasets (Zhao, G., Li, Y., Zhou, L., Gao 2022). While it is beyond the scope of this study to use and compare multiple gridded climate datasets, it is still important to discuss the uncertainty associated with the use of gridded climate datasets (Albano et al. 2022) when modeling open water evaporation.

For consistency across the NFS, gridMET (Abatzoglou 2013) is chosen as the meteorological dataset for all open water evaporation modeling analyses, and all other modeling components in the NFS. Validation of gridMET interpolated climate grids with station observations found the median MAE for maximum and minimum temperatures to range from 1.7 to 2.3 ˚C (Abatzoglou 2013). gridMET was found to have a slight cold bias in the Klamath Basin for minimum air temperature estimation, while it had a slight warm bias for maximum air temperatures, especially in the summer months (Abatzoglou 2013). gridMet estimated wind speeds are shown to have a positive bias in forested areas, whereas bias and correlations are better captured in non-forested landscapes such as those down by Lower Klamath and Tule NWR. gridMet uses downward shortwave radiation generated from the North American Land Data Assimilation System (NLDAS-2; Mitchell et al. 2004). Some studies have shown that NLDAS-2 shortwave radiation shows a positive bias over much of North America (Pinker, R.T. et al. 2003).

In addition, the resolution of a gridded dataset can impact the amount of uncertainty associated with the data. The resolution of the gridMET meteorological dataset is 4 km. In mountainous areas, such as along the western border of the model domain where the Cascade Mountains lie, 4 km is not always sufficient to properly characterize precipitation and temperature heterogeneities. Many of these lakes and reservoirs are located in the mountains and are also much smaller than 4 square km. Thus, the spatially averaged gridMET data that was used over the reservoir could contribute to model uncertainty, especially for the smaller reservoirs or lakes located in the mountainous areas.

# VI. Summary and Conclusions

This study was prepared by the Bureau of Reclamation (Reclamation) Technical Service Center (TSC) as part of the Klamath Natural Flow Study (NFS). In 2020, Reclamation was tasked with estimating refined natural streamflow estimates throughout the Klamath River Basin in a comprehensive NFS in response to comments on a previous NFS generated by the NRC (National Research Council 2008). In this study, natural streamflow is defined as the streamflow that would have occurred in the absence of land use changes (e.g., agriculture, forestry, etc.), major development (e.g., roads, railroads, municipalities, etc.), and water management (e.g., dams, hydroelectric plants, etc.). The purpose of the NFS is to use current science, methods, and tools to develop revised natural streamflow estimates for the Klamath River Basin between WY 1981 and WY 2020. As part of this larger NFS, we quantify open water evaporation rates and volumes at 13 different lakes and reservoirs across the Klamath Basin under two conditions:

- **Pre-development Conditions** are defined as the landscape and hydrologic conditions that existed around 1900, prior to major development of the region for irrigated agriculture, forestry, and other purposes.

- **Current Conditions** are defined as the landscape and water demand conditions that occurred throughout the past four decades, as a result of land use, development, and water management practices.

The open water evaporation models are developed for all man-made reservoirs in the Upper Klamath Basin (Copco 1, Gerber Reservoir, Howard Prairie Reservoir, Hyatt Reservoir, Iron Gate Reservoir, JC Boyle Reservoir, and Lost River Basin small reservoirs), any natural lakes that were enlarged due to the construction of a dam (Clear Lake, Fourmile Lake, and Lake Ewauna), and shallow lakes that were dewatered for the purposes of agriculture (Lower Klamath and Tule National Wildlife Refuges). To estimate daily, monthly, and annual lake and reservoir surface water evaporation at each site, we implement the Daily Lake Evaporation Model (DLEM, Zhao et al. 2023).

DLEM simulations representing both current and pre-development conditions are conducted from January 1, 1979 through September 30, 2020, using gridMET forcing data (Abatzoglou 2013). Results from January 1, 1979 to September 30, 1980 are used for model spin-up and removed. Current conditions daily average depths for each lake or reservoir are determined using one of three approaches: observed water elevation timeseries (Reclamation 2021c) and area capacity curves, from objective water levels (U.S. Fish and Wildlife Service 2016), or operating procedures (PacificCorp 2004). Timeseries of open water surface areas, used to estimate daily volumetric evaporation loss, are constructed from the GLEV remotely sensed surface area timeseries database (Zhao, G., Li, Y., Zhou, L., Gao 2022).

Pre-development simulations are conducted using natural average depths and surface areas determined from historical maps and studies (table 3) and run using current climate forcings. Pre-development evaporation rates and volumes are estimated for Upper and Lower Klamath Lake (UKL and LKL respectively), Lake Ewauna, Tule Lake, Fourmile Lake, and Clear Lake at estimated low and high water levels if available.  Pre-development surface areas for LKL and Tule are significantly larger than current conditions due to the drainage of wetlands and open water areas for agricultural purposes. Pre-development surface areas of UKL and Lake Ewauna are fairly similar to current conditions, although the construction of Link River Dam has moderated flow between the two waterbodies. Construction of the dam at the outlet of Fourmile Lake approximately doubled the surface area from pre-development to current conditions, although in comparison to UKL, Fourmile Lake is quite small in area. The construction of the dam at Clear Lake also increased its surface area from pre-development conditions by approximately 20% to 60% depending on low or high pre-development water levels.

DLEM results suggest that under current conditions daily evaporation volumes from all modeled 13 lakes and reservoirs range from just over 36 acre-feet in January to 2.5 thousand acre-feet (TAF) around July (figure 30). In comparison, pre-development daily evaporation totals peak at 3.5 TAF for low water simulations and 4.5 TAF for high water simulations. Despite there being many more waterbodies under current conditions due to the construction of dams, the draining of large shallow lakes like Tule and Lower Klamath leads to less volumetric evaporation loss overall under current conditions. On an annual timescale, it appears that upwards of 156–370 TAF more evaporation occurred during pre-development conditions than occurs presently (figure 31).

In conclusion, the evaporation rates and volumes presented here comparing current and pre-development conditions should be used while understanding various uncertainties associated with model development and how sensitive DLEM is to each uncertainty. Results from sensitivity analyses indicate average daily evaporation rates varied by less than 10 percent from the standard historical rate when exploring the impact of wind speed, fetch, and spatially averaging climate data.

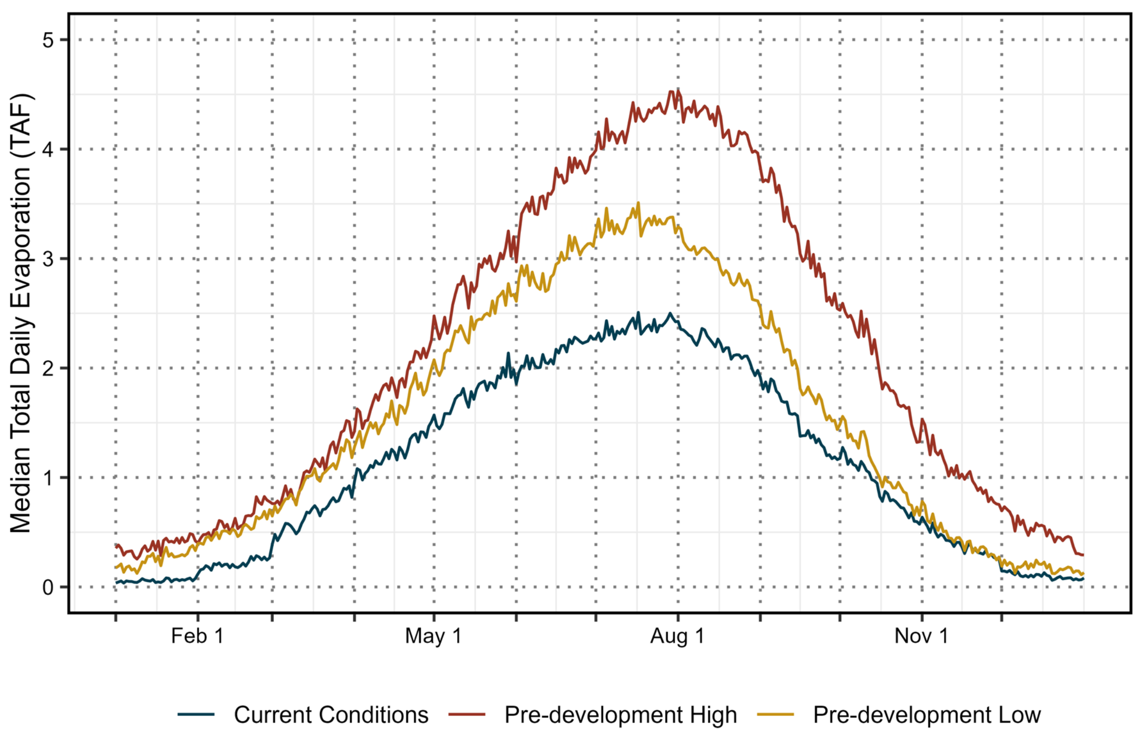



**Figure 30.—The median total daily volume of evaporation (in thousand acre-feet) from WY 1980 to WY 2020 from all lakes and reservoirs combined under current conditions (blue), pre-development high water level conditions (red), and pre-development low (gold) conditions.**

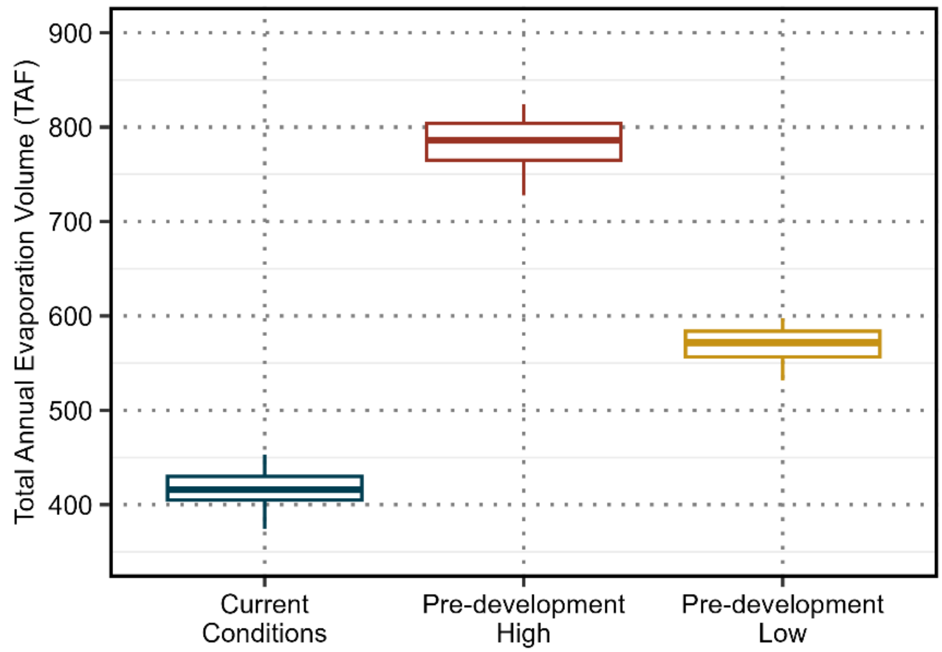



**Figure 31.—The distribution of the volume of evaporated water in one wateryear from all lakes and reservoirs under current (blue), pre-development high (red), and pre-development low (gold) conditions from WY 1981 through WY 2020. The box limits correspond to the 25th and 75th quartiles and the horizontal line within the box represents the median. Whiskers extend to 1.5 ± the interquartile range. Outliers are represented by black filled circles.**

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# Appendix A

Supporting Figures and Tables – Open Water Evaporation Modeling

Table A- 1.—The historic time periods associated with each observed Upper Klamath Lake configuration

| UKL Configuration | Time Period |
|---|---|
| UKL w/o Caledonia, Tulana, or Goose Bay | 8/31/1980–7/7/2006 |
| UKL w/ Caledonia | 7/8/2006–12/31/2006 |
| UKL w/o Caledonia, Tulana, or Goose Bay | 1/1/2007–10/30/2007 |
| UKL w/ Tulana | 10/31/2007–11/17/2008 |
| UKL w/ Tulana and Goose Bay | 11/18/2008–12/31/2020 |

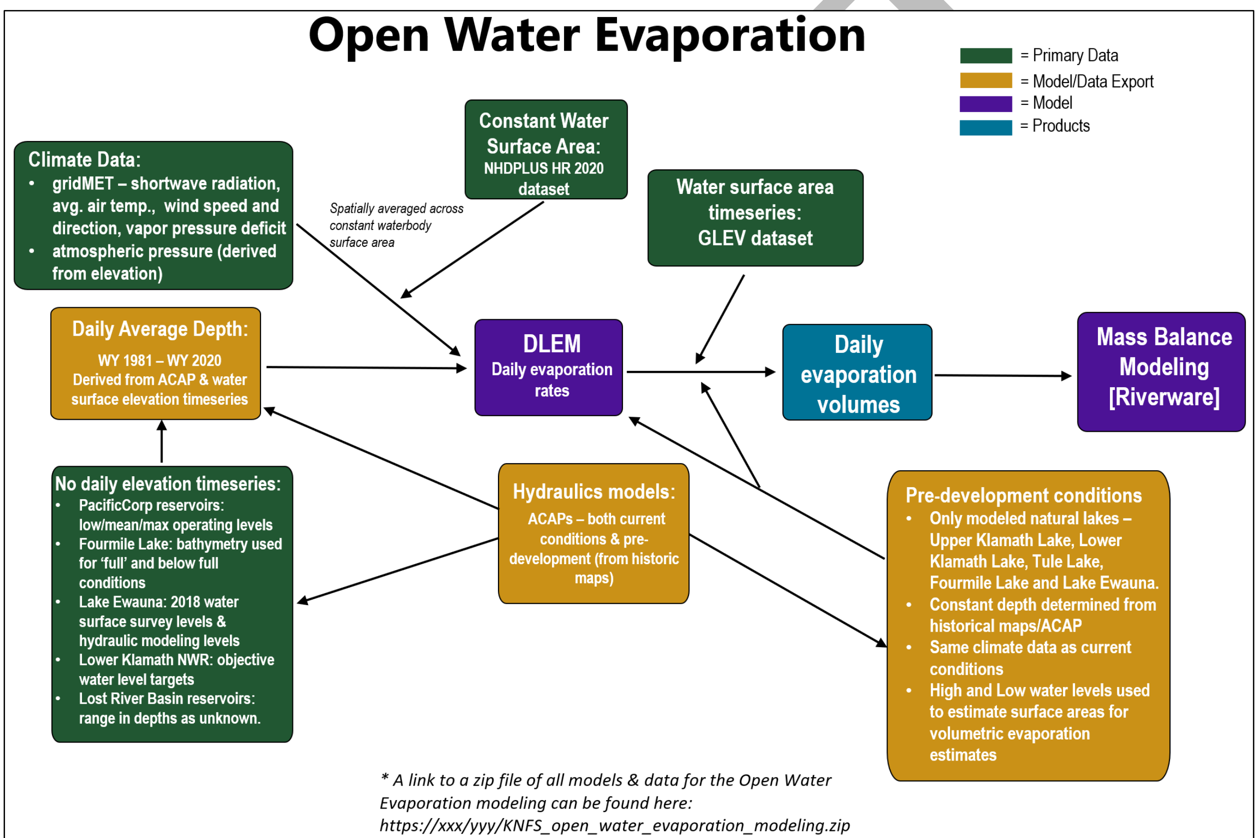


Figure A-1.—Schematic detailing the inputs and outputs from the NFS open water evaporation modeling component.

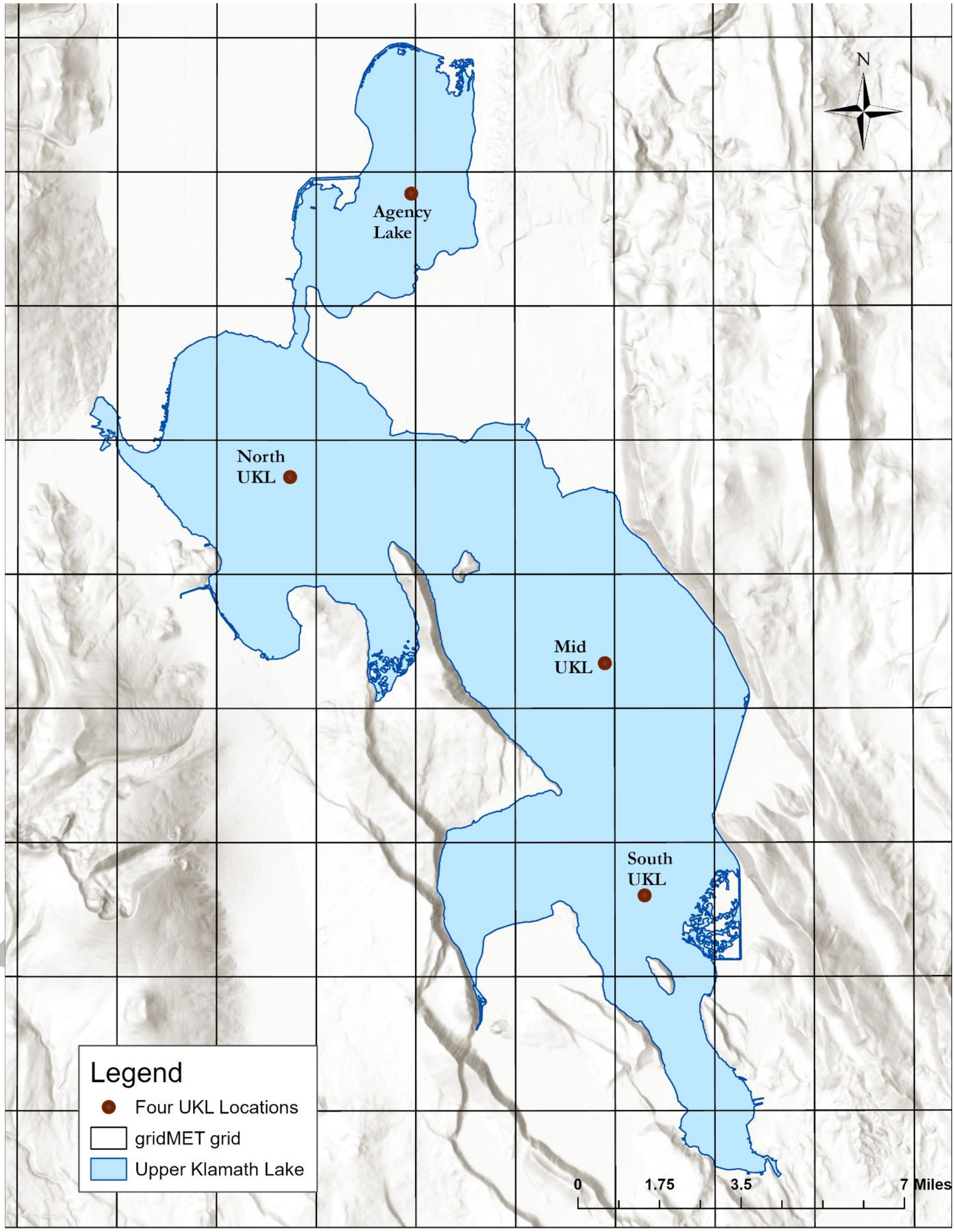


**Figure A-2.—Four locations across UKL for which the uncertainty associated with using area-averaged climate data is conducted.**

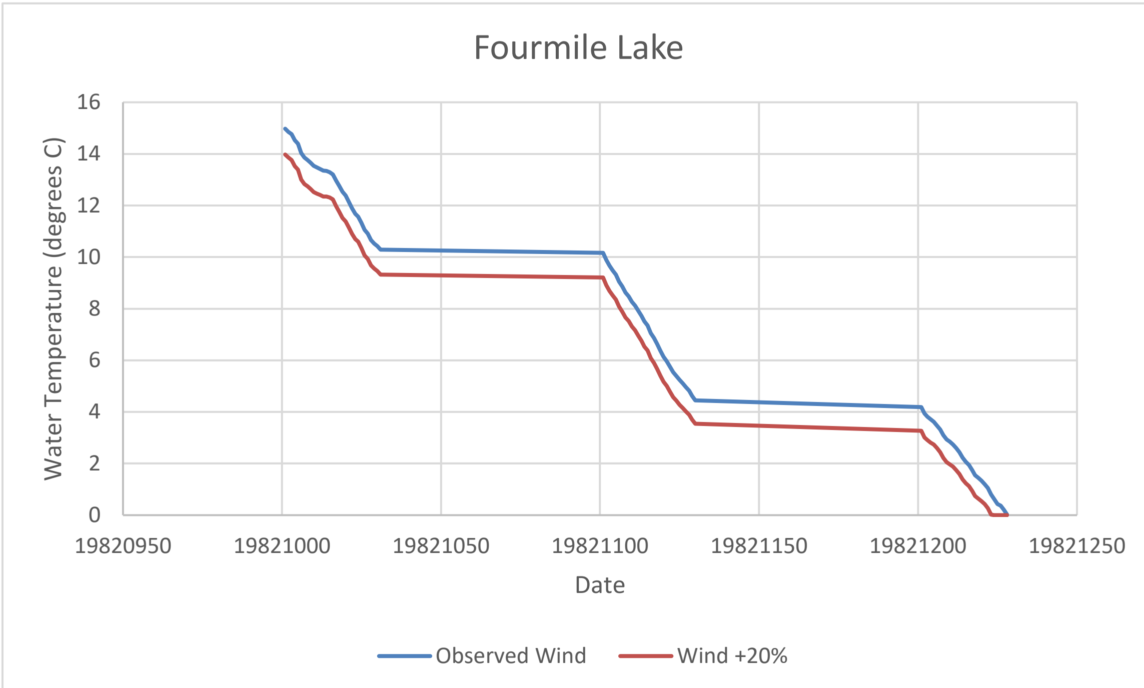


**Figure A-3.—A timeseries of DLEM-simulated water temperatures at Fourmile Lake when using observed wind speeds (blue line) and increasing the daily observed wind speed by 20 percent (orange line) from September 1982 through December 1982.**