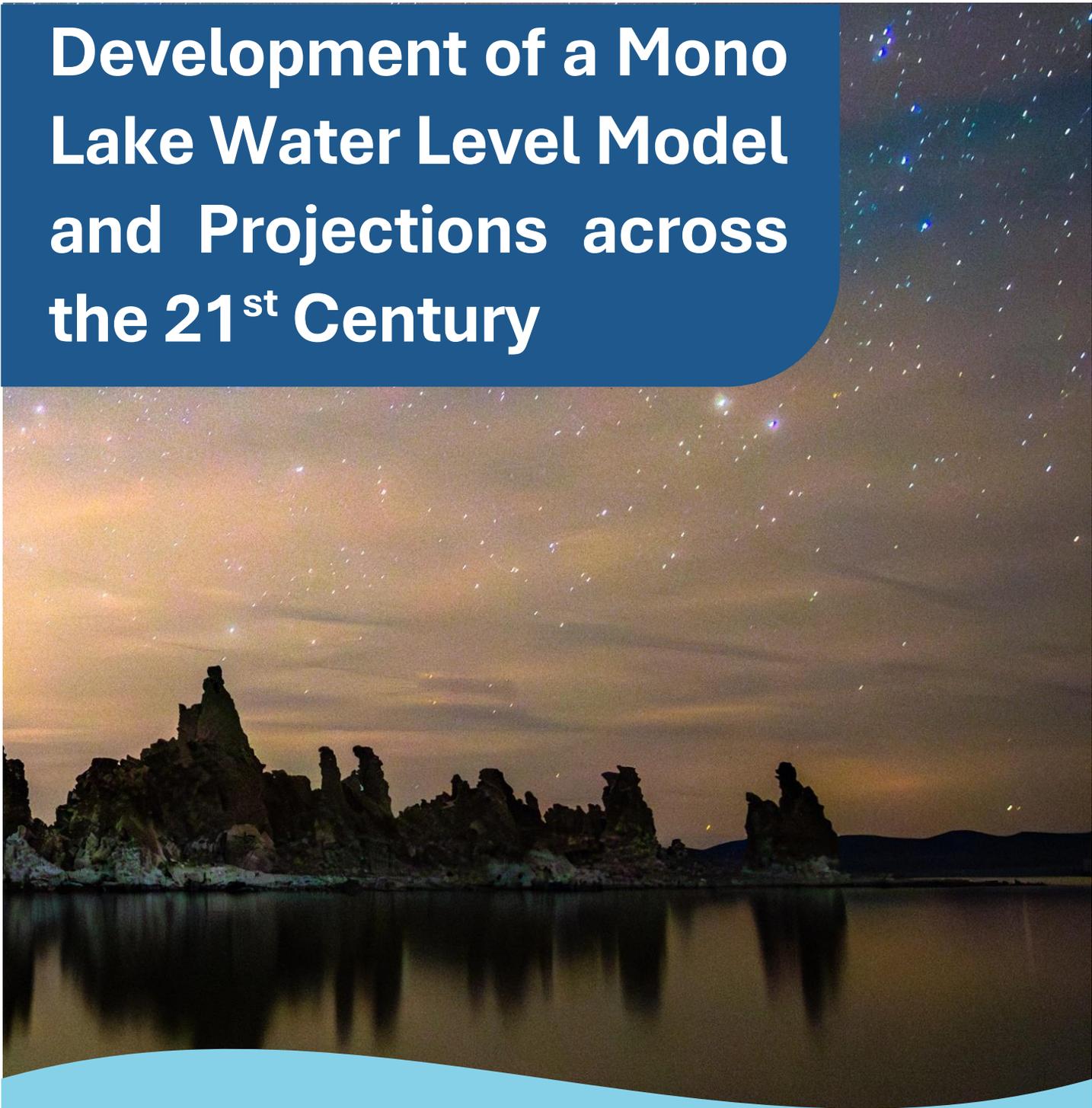# Development of a Mono Lake Water Level Model and Projections across the 21st Century

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Section: Division of Water Rights

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ABBREVIATIONS

Abbreviation	Meaning
ac-ft	ac-ft
CA5	California's 5th Climate Change Assessment
CCS	Center for Climate Science
CDFW	California Department of Fish and Wildlife
CMIP6	Coupled Model Intercomparison Project Phase 6
D-1631	Decision 1631
ECMWF	European Center for Medium-range Weather Forecasting
eSTREAM	Enhanced Stream Analysis Model
ERA5	ECMWF Reanalysis Version 5
ERA5-WRF	ERA5 downscaled by WRF, and bias corrected to station data
ET	Evapotranspiration
ft	feet
GCM	General Circulation Model
IFR	Instream flow requirements
IPCC	Intergovernmental Panel on Climate Change
LADWP	Los Angeles Department of Water and Power
LAA	Los Angeles Aqueduct
LOCA2-Hybrid	Localized Constructed Analogs version 2 Trained with WRF
MBOP	Mono Basin Operations Plan
MLTWG	Mono Lake Technical Working Group
MLWB	Mono Lake Water Budget Model
MLC	Mono Lake Committee
Noah-MP	Noah-Multiparameterization
P	Precipitation
RCM	Regional Climate Model

RYT	Runoff Year Type
SEF	Stream Ecosystem Flows
SRF	Stream Restoration Flows
SSP	Shared Socioeconomic Pathway
SWE	Snow Water Equivalent
SWRCB	(California) State Water Resources Control Board
T	Temperature
UCLA	University of California, Los Angeles
UCLA-MLM	UCLA Mono Lake Model
WL	Water Level
WRF	Weather Research and Forecasting Model

DEFINITIONS

6,391 ft: This is the transition water level that was intended to be reached approximately 20 years after D-1631, which was adopted by the SWRCB in September 1994. When this water level is reached, the post-transition export criteria go into effect.

6,392 ft: This is the average long-term target water level determined in D-1631 to protect public trust resources at Mono Lake.

Amended Licenses: The authority to divert water goes back to 1940. D-1631 provided master requirements, and the amended licenses formalized the new conditions under which LADWP could divert water from the Mono Basin, incorporating environmental protections and revised flow requirements for the streams feeding Mono Lake. State Water Board Orders WR 98-05 and 98-07 required LADWP to implement restoration, monitoring and Grant Lake Reservoir operation plans as part of a Stream Restoration and Monitoring Program. State Water Board Order WR 2021-0086 Amended Licenses 10191 and 10192 incorporated the 2013 Mono Lake Basin Restoration Settlement Agreement between LADWP and interested parties.

Bias Correction: Process of adjusting model outputs to remove systematic errors (bias) so that the results more accurately reflect observed or true values.

CA5: California Fifth Climate Assessment. A comprehensive, state-led research initiative designed to advance actionable science and strengthen understanding of local climate impacts in California. Mandated by Senate Bill 1320, it provides updated data, models, and nine regional reports to guide policies, investments, and community-led resilience actions across California. This report primarily refers to the dataset from CA5, which was used for analysis this study.

Climate Change: Climate change refers to statistically significant, persistent changes in the mean state and variability of the climate system over decades or longer, resulting from internal variability inherent to the climate system and/or from changes in external anthropogenic forcings (e.g., greenhouse gas emissions, aerosol emissions, and land-use and land-cover change).

CMIP6: The sixth phase of the Coupled Model Intercomparison Project, providing climate model simulations to study past, present, and future climate changes.

D-1631: The SWRCB decision adopted in 1994 required LADWP to reduce the amount of water it diverted from the Mono Basin in order to restore Mono Lake to an average elevation of 6,392 ft. D-1631 states, "This decision also amends Los Angeles' water right licenses to include specified water diversions criteria which are intended to gradually restore the average water elevation of Mono Lake to approximately 6,392 ft above mean sea level in order to protect public trust resources at Mono Lake."

Downscaling: A method for deriving high-resolution climate data from coarse global climate models (GCMs).

Emission Scenario: A pathway of projected levels of greenhouse gas emissions over time, which for CMIP6 are based on socioeconomic scenario pathways (SSPs). A range of intermediate to very high emission scenarios are assessed in this report since the actual emission scenario that will occur is unknown.

ERA5: ERA5 is the fifth-generation global atmospheric reanalysis dataset produced by the European Centre for Medium-Range Weather Forecasts (ECMWF). It provides 31 km resolution, consistent, and comprehensive estimates of historical weather and climate variables by assimilating a vast array of observations into numerical weather prediction models. See "Reanalysis."

ERA5-WRF: A 3 km version of ERA5 produced by the UCLA Center for Climate Science and UC Scripps. ERA5-WRF was developed using a numerical weather model (Weather Research Forecasting, WRF) to downscale ERA5 from its native 31 km resolution to a 3 km resolution using physics-based mass and conservation representation of the atmosphere and its land-surface interactions. This downscaling process was followed by bias corrections to precipitation, temperature, wind, shortwave solar, and humidity stations available throughout California.

Exports: Surface water exports are made by diverting water from tributary streams that would otherwise flow into Mono Lake. The diverted water is stored in Grant Lake Reservoir, with some of that water being diverted out of the basin via the Mono Craters Tunnel. Exports out of the basin are directed into the Owens River and then the Los Angeles Aqueduct. Exports include surface water exports and groundwater exports; however, unless otherwise stated, exports is used to refer to surface water exports.

Export Criteria: Export criteria determine the maximum amount of water in acre-feet that LADWP can export in a runoff year. Export amounts are determined by current D-1631 criteria. While groundwater exports can occur via the Mono Craters Tunnel, the export criteria is assumed to apply to surface water exports.

Four-Creek Flow: The combined flow from Lee Vining, Walker, Parker, and Rush Creek which determines the runoff year type.

GCMs: Global Climate Models (also referred to as General Circulation Models), which are complex mathematical models used to simulate Earth's climate system and estimate climate change.

Hydrology Model: Here, a physics-based hydrology model is used to simulate the processes governing the fluxes and storages of water within the hydrologic cycle across spatial and temporal scales. This model is used to represent the land surface response to meteorological forcing and to evaluate the effects of climate change on natural runoff conditions throughout the Mono Basin. This provides a critical term for the Mono Lake Water Budget Model. Human alterations are represented in the Water Budget Model, but not the hydrology model.

Hydroclimate Projections: This term is used throughout the report to reflect global climate model (GCM) projections of precipitation, evaporation, and runoff conditions throughout the Mono Basin, which influence Mono Lake water level.

IFR: Instream flow requirements, including stream restoration flows (SRF) and stream ecosystem flows (SEF). These requirements ensure that sufficient water remains in the natural system to sustain the health and function of aquatic ecosystems.

Internal Variability: Natural fluctuations (e.g. El Niño Southern Oscillation) in the climate system that occur without external forcings (changes in the Earth's energy budget) like greenhouse gas emissions or volcanic eruptions.

LADWP: The Los Angeles Department of Water and Power is the municipally owned utility of the City of Los Angeles, responsible for the generation, transmission, and distribution of electricity and the supply, treatment, and delivery of potable water. LADWP exports a portion of the water from the Mono Basin to a provide a portion of the water supply for the City of Los Angeles.

Lee Vining Conduit: The Lee Vining Conduit, completed in1941, diverts water from Lee Vining Creek into Grant Lake. This water then flows towards Mono Lake or out of the Mono Basin via the Mono Craters Tunnel. Historically, the Lee Vining Conduit also diverted water from Walker and Parker Creek; however, stream ecosystem flows no longer allow diversions from Walker and Parker as of 2020.

Likelihood: The likelihood or probability of a condition occurring is assessed by the percentage of GCMs that agree on a specific change. This metric is commonly used to evaluate the likelihood of being at or above a particular water level. Descriptions of likelihoods presented throughout the report are based on numeric ranges used by the IPCC and the National Climate Assessment (**Table 3-2**).

LOCA2-Hybrid: Statistical downscaling technique called Localized Constructed Analogs version 2 (LOCA2) that is trained on dynamically downscaled GCM data from WRF. This report uses atmospheric projections produced from this method at a 3 km resolution.

Modeled Observations: Representation of observed atmospheric and hydrologic conditions that occurred across the Mono Basin from 1955 to 2020 (see ERA5-WRF).

Model Resolution: Atmospheric data are typically produced at the global scale with coarse spatial resolution (e.g., grid spacing on the order of ~100 km). Downscaling is a method used to derive higher-resolution atmospheric information (e.g., grid spacing on the order of ~3 km) for specific regions of interest by dynamically or statistically refining coarse-resolution model outputs.

Mono Craters Tunnel: An 11 mile long, roughly 9 ft diameter tunnel completed in 1939. This tunnel exports water from the Mono Basin that would otherwise naturally flow into Mono Lake. The Mono Craters Tunnel also intercepts and exports roughly 5,500 acre-feet/year of groundwater sourced from the Mono Basin.

Mono Lake Technical Working Group (MLTWG): Meetings which included technical experts from several participating organizations, including LADWP, MLC, CDFW, and the SWRCB. Over 12 technical group meetings were held to discuss how to simulate Mono Lake, evaluate its recovery, and to develop export criteria alternatives to consider from September 2023 and April 2024.

MLWB: Mono Lake Water Budget Model. This is the water budget model of Mono Lake developed by UCLA CCS and described in this report.

MBOP: Mono Basin Operations Plan, developed and written by LADWP to provide guidelines for LADWP operations in the Mono Basin as a part of the requirement from the 2013 Mono Basin Settlement Agreement and further SWRCB Amended Licenses.

Natural Runoff: The flow of water that would occur in a watershed basin without human alterations, such as damming, diversions, or other infrastructure. It is an idealized measure of the water generated by natural processes, assuming no human interference. Natural runoff is approximately the same as unimpaired runoff.

Transition Criteria: Criteria outlining allowed LADWP surface water exports until Mono Lake reaches 6,391 ft. These criteria were set in D-1631. Once this water level is reached, the post-transition export criteria go into effect.

Post-Transition Criteria: Criteria outlining allowed LADWP exports once Mono Lake reaches the transition water level of 6,391 ft. These criteria were set in D-1631. The post-transition expectation is to ensure a long-term average water level of 6,392 ft.

Reanalysis (ERA5): Reanalysis data, such as ERA5, is created by feeding historical observations (from satellites, weather stations, and other sources) into a numerical weather model, providing detailed data on atmospheric, land, and oceanic conditions over time. Reanalysis data can provide a more comprehensive set of climate variables than observed data and is more geographically and temporally complete and consistent.

Recovery: An increase in Mono Lake's water level. Broadly used in the context of Mono Lake's water level being higher than the April 1st, 2024 water level of 6,383.7 ft.

Regulated/Impaired Flow: The flow of water includes modifications to that flow made by human structures, such as dams or reservoirs for purposes like irrigation, flood control, or hydropower.

RY: Runoff Year, which occurs from April 1st YYYY to March 31st YYYY+1

RYT: Runoff Year Type, which includes seven year types that were defined in MBOP: Dry, Dry-Normal I, Dry-Normal II, Normal, Wet-Normal, Wet, and Extreme-Wet. Runoff year types are defined based on four-creek flow conditions. In this report RYTs were simplified to six year types by combining the range of flow conditions experienced in Dry-Normal I and Dry-Normal II since their total annual flow requirements are roughly the same.

SSP: Shared Socioeconomic Pathways, which are scenarios used to project future climate change based on a range of potential future socio-economic choices and their impact on greenhouse gas emissions, climate change mitigation and other climate impacts.

UCLA-MLM: UCLA Mono Lake Model, which includes both the hydroclimate forcing data and water budget model developed to represent Mono Lake water level.

Water Budget Model: A modeling tool used to quantify the movement of water through a system (usually a watershed or basin) by representing each component of the system's inflow (or supply) and outflow (or demand). The basic components usually include precipitation, evaporation, natural runoff and changes in storage.

Wrapped Runs: Approach in which historical conditions as they were observed are reevaluated by considering how Mono Lake water level would have evolved with a different start year. For example, rather than solely evaluating 1971 to 2020 hydroclimate conditions as they actually occurred, a wrapped run will also include 1972-2020,1971; 1973-2020, 1971-1972; etc. For a time period like 1971 to 2020, this leads to 50 unique hydroclimate sequences. This approach shows how Mono Lake water level conditions respond to variations in weather, thus approximating the influence in internal variability.

ACKNOWLEDGEMENTS

EXECUTIVE SUMMARY AND OVERVIEW OF REPORT

Mono Lake is a unique and ecologically important terminal lake in California's Eastern Sierra Nevada. It is sustained by precipitation and runoff within the Mono Basin, with evaporation as its primary natural water loss mechanism. Since 1941, the Los Angeles Department of Water and Power (LADWP) has diverted surface water from the basin to support municipal water supply. By 1990, these diversions had lowered the lake level by more than 40 feet (ft) and reduced its volume by approximately 50%, resulting in increased salinity, degraded habitat for nesting and migratory birds, and exposed alkali lakebed sediments that contribute to air quality concerns (Weins, 1993).

In response, *National Audubon Society v. Superior Court* (1983) *33 Cal.3d 419* expanded the definition of California's public trust doctrine, which protects environmental resources for public benefit, to include streams flowing into navigable waterways, even if water rights were already allocated to such streams. The California Supreme Court held that the state has a duty to take the public trust into account in the planning and allocation of water resources and to protect public trust uses when feasible. Even after an appropriation has been approved, the public trust imposes a duty of continuing supervision. Following this court case, the State Water Resources Control Board (SWRCB) adopted Decision 1631 (D-1631) in September 1994 when Mono Lake's water level was roughly 6,375 ft.

D-1631 concluded that maintaining Mono Lake at an elevation of 6,392 ft would protect critical public trust resources, including air and water quality, ecosystem health, habitat for nesting and migratory birds, and recreational and scenic values, while still allowing for some municipal water for LADWP. The decision made in 1994 established transition export criteria intended to raise the lake to a transition level of 6,391 ft within 20 years, followed by a post-transition export criteria to sustain a long-term average water level of 6,392 ft. More than 30 years since D-1631, however, the lake has yet to reach the 6,391 ft threshold, measuring 6,383.3 ft as of April 1, 2025. This lack of recovery, despite LADWP's adherence with D-1631 export limits, raises concerns about the suitability of the existing export criteria, particularly in the context of changing climate conditions.

In 2022, Mono Lake dropped to roughly 6,378.5 ft, prompting urgent requests from the Mono Lake Committee (MLC), the Mono Lake Kootzaduka'a Tribe, and California Department of Fish and Wildlife (CDFW) for SWRCB to take immediate action to prevent further lake declines. Although above average precipitation in water year 2022-2023 helped the lake rebound to approximately 6,383 ft, it remains nearly nine ft below the long-term water level objective outlined in D-1631.

In light of the SWRCB's ongoing responsibility to protect public trust resources and support Mono Lake's recovery amid a changing climate, the SWRCB contracted the University of

California, Los Angeles (UCLA) Center for Climate Science (CCS) to conduct updated hydrological evaluations related to Mono Lake. UCLA CCS was selected for its expertise in producing state-of-the-art climate data, and its experience in assessing climate-driven changes in water systems in collaboration with stakeholders. To support this work, UCLA CCS developed a process-based water budget model, which represents the physical processes that drive the hydrologic cycle in the Mono Basin, including precipitation, runoff, evaporation, streamflow and groundwater exports. The water budget model also incorporates the effects of LADWP operations on flows into Mono Lake. Specifically, the water budget model represents inflows into Mono Lake from the Mono Basin streams, direct precipitation onto the lake, evaporation from the lake surface, and LADWP surface water exports from streams that would otherwise flow into Mono Lake. The water budget model reproduces observed Mono Lake conditions with a mean absolute error of approximately 0.48 ft for the 1994 to 2020 period – a reasonably low error for assessing Mono Lake's water level in the context of D-1631 water level objectives.

The UCLA Mono Lake Model (UCLA-MLM) was developed to assess how climate-driven changes and existing and alternative export criteria influence Mono Lake's water level throughout the 21st century. Unlike existing approaches that rely solely on historical data, which may no longer reflect current or future climate conditions, this model integrates high-resolution climate projections developed for California's 5th Climate Assessment (CA5). UCLA-MLM's flexible framework allows for analysis using various export criteria and potential future climate conditions, enabling the assessment of future lake conditions under a range of possible outcomes. This work was developed in close coordination with the SWRCB, with valuable input from partners including LADWP and MLC.

The UCLA MLM is a complex, technical tool that incorporates climate projections and detailed hydrologic processes. It was developed for use by scientists, engineers, and water-management professionals with experience in climate and hydrologic modeling and familiarity with the broader ecological challenges facing Mono Lake. As such, the model is not intended for general public use or simplified interpretation. To support transparency and understanding, summaries and key findings are provided to explain what the model shows and how it informs management decisions. The UCLA MLM is accessed through a User Interface, which will be made available to interested parties by request. The SWRCB may also coordinate sessions to demonstrate UCLA-MLM use and functionality.

This report describes the design and capabilities of the UCLA-MLM and presents an evaluation of how Mono Lake's water level may be affected by climate change and various export scenarios. The analysis focuses on three greenhouse gas emission scenarios from the Intergovernmental Panel on Climate Change's (IPCC's) Shared Socioeconomic Pathways (SSPs) to drive the climate change projections: an intermediate scenario (SSP2-4.5), an intermediate-high or business-as-usual scenario (SSP3-7.0), and a very high scenario (SSP5-8.5). SSP2-4.5 and SSP3-7.0 were selected for this report given their relatively high likelihood of being realized, while SSP5-8.5 provides insight into a stronger but unlikely emission

scenario. Each emission scenario includes 11 downscaled Global Climate Models (GCMs) that were selected as a part of CA5 based on their ability to represent conditions relevant to California weather. As with the uncertainty of which emission scenario will be realized, there is uncertainty in how each GCM's precipitation and other atmospheric variables will respond to emissions. As such, each GCM projection in this study is considered plausible and therefore useful in determining the overall likelihood of Mono Lake's water level. The resulting ensemble of GCMs used in the UCLA-MLM provides a range of plausible future outcomes, supporting more informed decision-making by accounting for uncertainty in long-term climate projections.

UCLA-MLM evaluates Mono Lake's response to a range of transition and post-transition export criteria under changing climate conditions. This includes the Existing Export criteria, No Exports, and a proposed list of alternative transition and post-transition export criteria (**Table 4-5**). Alternative export criteria were developed as part of the Mono Lake Technical Working Group (MLTWG) meetings, a technical collaboration including MLC, LADWP, CDFW, SWRCB, UCLA and other key parties. This report assesses 84 export criteria and to simplify referencing, each transition and post-transition export criteria was assigned a reference code, detailed in **Section 4.2**. This report also assesses the lake response under conditions without human-induced climate change. This analysis underscores the importance of accounting for both historical and projected climate shifts that have already influenced, and are likely to continue influencing, Mono Lake's water level.

A summary of key findings, final thoughts, and a general outline of the report are presented below. Descriptions of likelihoods presented throughout the report are based on numeric ranges used by the IPCC and the National Climate Assessment (**Table 3-2**).

Additional Resources

For readers primarily interested in the findings and conclusions of this study or those looking for a more succinct and accessible overview and important takeaways, an additional document was created, titled *Project Summary and Key Findings for Policy Makers*. This summary was created explicitly for policy makers, organizers, community advocates and members of the public.

The *Appendix* for this main report contains details and figures that may be of interest to technical experts but are not necessary to understand the overall workflow and findings outlined in the main report.

The UCLA MLM is accessed through a User Interface, which will be made available to interested parties by request.

Key Findings

1. Climate change has already had an impact on Mono Lake's water budget.

Mono Lake's water budget has already been altered by climate change, with recent historical and projected future trends showing increased evaporation rates over pre-1990 conditions (Figure 3-2). Modeling results indicate that since the 1950s, climate change alone is responsible for roughly a 2.6 ft reduction in the 2024 lake level, albeit there is uncertainty in this estimate (Appendix Figure C-24). Although future climate projections suggest that precipitation totals will increase, it is likely that increasing evaporation rates will continue to outpace precipitation gains, resulting in a net water loss for Mono Lake. For UCLA-MLM simulations starting in 2024, reductions in water level across the remainder of the 21st century can reach up to 6.5 ft due to climate change, depending on the emission scenario (Figure 4-3). UCLA-MLM evaluations show that climate change substantially reduces the likelihood that Mono Lake exceeds 6,391 ft compared with simulations that exclude climate change. For example, UCLA-MLM results indicate that climate change could reduce the likelihood of Mono Lake exceeding 6,391 ft by 15 to 42% over the next 30 years (Table 4-3).

2. Existing export criteria are unlikely to achieve Mono Lake's long-term water level goals.

Based on the range of emission scenarios, UCLA-MLM simulations indicate that the existing export criteria offer about a one-in-three chance (29–38%) that Mono Lake will exceed 6,391 ft within the next 40 years (by 2064; Table 4-4). Even with no exports, the peak likelihood of exceeding 6,391 ft water level within the same timeframe is only modestly higher (42–73%). These findings underscore that, even without exports, climate change poses significant challenges to meeting the D-1631 decision of maintaining an average water level of 6,392 ft. Overall, the results show that current export criteria, without revision, are unlikely to reliably restore and sustain the target lake level.

3. Strategic adjustments to transition and post-transition export criteria can aid recovery while preserving exports.

UCLA-MLM simulations demonstrate that alternative export approaches can increase the likelihood of Mono Lake being above 6,391 ft, as compared to the existing exports outlined in D-1631. The degree of recovery depends on both the transition and post-transition export criteria chosen. For example, reducing exports during the transition period can accelerate the timing and likelihood that Mono Lake reaches 6,391 ft (Figure 4-6, Table 4-9). Several post-transition export criteria options (including option PT3) balance lake recovery with exports; these options come closer to achieving the D-1631 water level objective, as compared to the post-transition export criteria outlined in D-1631 (Table 4-10). Generally, as expected, the likelihood of the water level being above 6,391 ft increases as exports in both the transition and post-transition periods decrease (Table 4-11). Even if the transition to 6,391 ft is lengthy or not reached, there are added benefits to public trust values from modifying the existing export criteria to support increases in Mono Lake's water level towards 6,391 ft.

Final Thoughts

Mono Lake's recovery remains a significant challenge, even in the absence of surface water exports. UCLA-MLM results demonstrate that while eliminating exports allows for the greatest likelihood for increasing the lake's water level, targeted changes to the export criteria can provide improved water level outcomes. For example, transition export criteria that limit exports to dry years paired with post-transition export criteria PT3 can achieve improved recovery outcomes. As compared to the existing export criteria, these proposed alternatives improve the likelihood that Mono Lake reaches and maintains a water level above 6,391 ft over the coming decades and support an adaptive approach to balancing water supply needs and ecological recovery. However, it is important to acknowledge that while modeling indicates that eliminating exports would yield higher likelihoods of lake level recovery under historical climate conditions, several climate projections suggest a drier future that could make it increasingly difficult to D-1631 water level objectives regardless of export criteria.

The export criteria evaluated in this report provide a baseline set of options, but do not represent the full range of possibilities. Ongoing analysis with the UCLA-MLM is intended to support continued collaboration and transparency. Most importantly, any consideration of revised export criteria should be informed by how the climate has changed, and is expected to continue changing, rather than relying solely on historical conditions. Decisions made in this context will help determine how Mono Lake can successfully be restored and preserved as a valuable ecological and public resource for generations to come.

General Overview of Report

This report is structured to provide a comprehensive analysis of Mono Lake's water budget, the impact of climate change, and the effectiveness of existing and alternative water management export criteria. It begins with **Section 1 (Introduction)** which outlines the historical context of the Mono Basin and the development of its export criteria, describes other existing models and introduces UCLA-MLM. **Section 2, (Development of the Mono Lake Water Budget)** details the development and performance of the water budget model and the forcing data used to represent observed conditions. **Section 3 (21st Century Hydroclimate Simulations)** outlines the Global Climate Model (GCM) projections used and their anticipated impacts on Mono Basin's precipitation, evaporation, and runoff. **Section 4 (Modeling Mono Lake's Water Level Under Existing Export Criteria)** examines how the lake responds to observed weather and climate change scenarios, under existing and alternative transition and post-transition export criteria. Finally, **Section 5 (Future Work)** includes information regarding the User Interface of the UCLA-MLM and ongoing research at the UCLA CCS, and **Section 6** provides a **Report Summary**.

For readers interested in learning about the UCLA-MLM development, **Sections 2** and **3** are relevant, while readers interested in results from the UCLA-MLM can refer to **Section 4**. Additional details associated with the UCLA-MLM development are provided in **Appendix A**, and additional figures that are of interest but not critical to the report are provided in **Appendix B** to **E**.

1 INTRODUCTION

The State Water Resources Control Board (SWRCB) contracted the University of California, Los Angeles (UCLA) Center for Climate Science (CCS) to develop the UCLA Mono Lake Model (UCLA-MLM), a hydrologic model designed to assess how Mono Lake level may respond to climate change and surface water management decisions across the 21st century. The model supports SWRCB's efforts to address drought resilience while balancing public trust resources in the Mono Basin.

Unlike earlier approaches that rely solely on observations, the UCLA-MLM integrates advanced climate projections from California's 5th Climate Assessment (CA5) and uses a flexible modeling framework to evaluate a wide range of climate conditions and export criteria. This allows for an assessment of future lake conditions under diverse hydrologic and surface water diversion criteria.

To inform the model's development, UCLA CCS worked closely with SWRCB and met extensively with experts from the Los Angeles Department of Water and Power (LADWP), Mono Lake Committee (MLC), California Department of Fish and Wildlife (CDFW), and others with long-standing knowledge of the Mono Basin. This collaborative approach, combined with state-of-the-art hydroclimate datasets, enabled an objective and scientific evaluation of Mono Lake's ability to recover under historical and projected climate conditions, and existing and alternative export criteria.

This section introduces the project and provides important background information. **Section 1.1** discusses the history of Mono Lake, outlining the events that motivated further evaluation of Mono Lake conditions and the involvement of UCLA CCS. **Section 1.2** describes other models used to simulate Mono Lake levels, highlighting UCLA-MLMs unique capabilities. **Section 1.3** provides an overview of UCLA-MLM.

1.1 Mono Basin Historical Conditions and Background

Mono Lake is a terminal saline lake located in California's Eastern Sierra Nevada (**Figure 1-1**). The lake is a vital ecological resource that contains no fish but supports a large population of brine shrimp and alkali flies that provide food for vast numbers of nesting and migratory birds. Islands in the lake protect a large breeding colony of California gulls, and the lake itself serves as a haven on the migration route for thousands of phalaropes and grebes. The Mono Lake Tufa State Natural Reserve provides includes tufa towers and spires on the lake's shores that are matters of geological and tourism interest, and the lake provides recreational opportunities such as canoeing on the lake and hiking in the surrounding the Mono Basin National Forest Scenic Area. Mono Lake depends on precipitation and runoff for its inflow. Under natural conditions, evaporation is the primary mechanism for the lake's water loss.

In the late 1930s and early 1940s, LADWP built the Mono Basin Extension, a system of conduits, reservoirs, and tunnels to export water from the Mono Basin. Since 1941, LADWP has diverted varying amounts of natural runoff from the Mono Basin into the Owens River and subsequently into the Los Angeles Aqueduct, which delivers water to the City of Los Angeles (**Figure 1-2**). From 1941 to 1990, these diversions drastically reduced inflows into Mono Lake, which contributed to more than a 40 ft drop in the lake's water level and roughly a 50% reduction in its volume (**Figure 1-3**).

Figure 1-1

Location of the Mono Basin relative to California. Colors represent elevation (meters). Red outline depicts the zoomed-in bounds shown in the right figure. The Mono Basin includes a mountainous high-elevation portion at its western edge that separates the Western Sierra Nevada from the Eastern Sierra Nevada. The majority of runoff that flows into Mono Lake comes from the western Sierra Nevada portion of the Mono Basin. The rest of the Mono Basin contains mountain terrain with a gently sloping gradient to the east of Mono Lake.
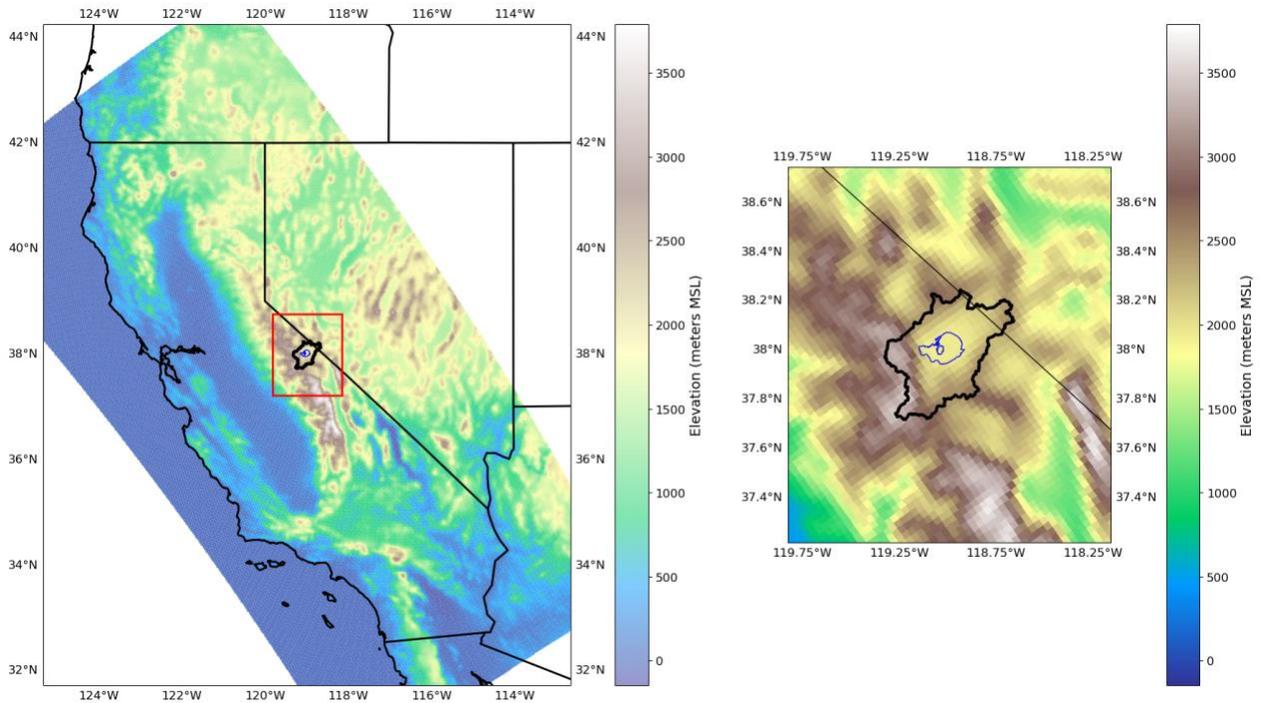
Figure 1-2

a) Map illustrating Los Angeles Aqueduct system and its supply watersheds. Water diverted from the Mono Basin, via the Mono Craters Tunnel, is exported into Owens River and eventually flows into the Los Angeles Aqueduct that supplies water to the City of Los Angeles. b) Aerial imagery of the Mono Basin with its primary water gains and losses (photo by Peter Essick). c) Images of Mono Craters Tunnel and Los Angeles Aqueduct (photo source; LADWP, 2022).
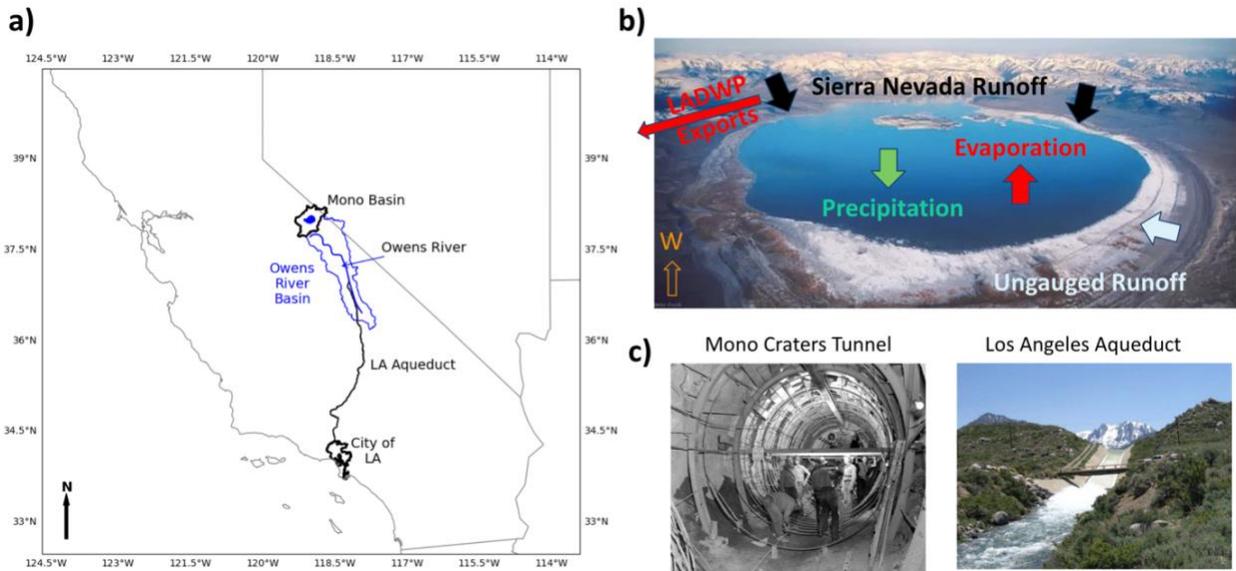
Figure 1-3

a) Changes in Mono Lake water level since LADWP exports began, with relevant water levels included as dashed horizontal lines. b) LADWP surface water exports. Both figures include the year Decision-1631 was adopted (September 1994) as a vertical grey line.
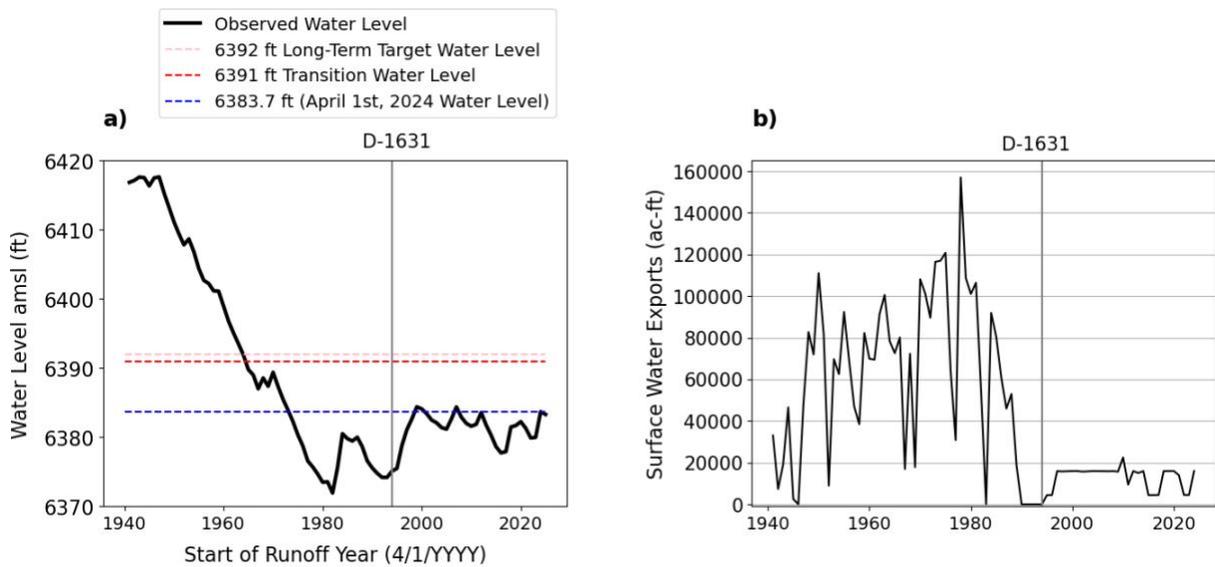
This drop in Mono Lake prompted litigation to preserve the lake's unique ecosystem and mitigate negative environmental impacts, such as increased salinity, that threatened vital habitats for nesting and migratory birds and other species, and air quality issues stemming from exposed lakebed dust. In 1983, the California Supreme Court ruled that the state has a duty to take public trust resources (natural resources which are of beneficial use to the public) into account in the planning and allocation of water and to protect public trust uses when feasible, even after an appropriation has been approved. The ruling required reconsideration of LADWP's water rights in light of public trust responsibilities and introduced a framework for balancing environmental preservation with water demand, which has influenced water management across the state.

In response, the SWRCB adopted Decision 1631 (D-1631) in 1994, which limited LADWP water exports from the Mono Basin, aiming to gradually restore the lake's water level. Using models, D-1631 established the objective of reaching a water level of 6,391 ft within 20 years and maintaining a long-term average water level of 6,392 ft thereafter. To achieve this objective, D-1631 outlined what is referred to throughout this report as the "Existing Export Criteria" or simply "Existing Exports" (shown in **Figure 1-4**). The Existing Exports include a transition period with export criteria that apply before the water level first reaches 6,391 ft and a post-transition period with export criteria that apply after Mono Lake's water level reaches 6,391 ft. The 6,391 ft elevation serves as a critical threshold within operational rules, marking a change between the lake's transition period and the lake's post-transition period. D-1631 stipulates that post-transition management should maintain 6,392 ft as the target level or public trust protection level.

Figure 1-4.

Surface water exports allowed by LADWP per D-1631 established in September 1994. Note, the arrow for 6,391+ ft water levels in the right figure, which represents the post-transition export criteria, indicates that any amount of water can be exported when the water level is above 6,391 ft as long as the Amended Licenses requirements (e.g. instream flows) are met.
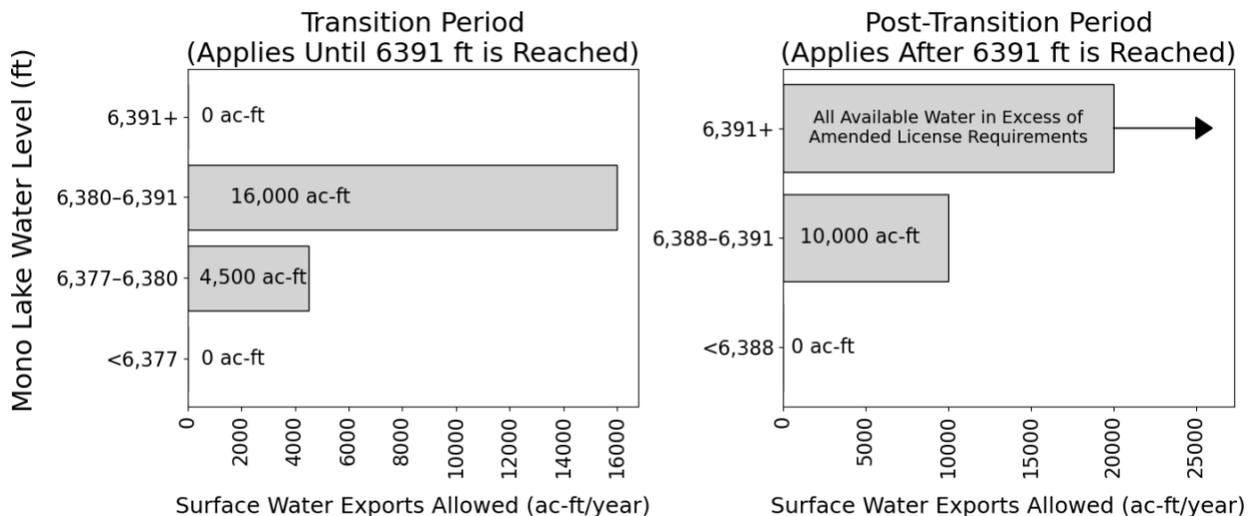
D-1631 concluded that maintaining a water elevation of 6,392 ft would allow some municipal water for LADWP while protecting Mono Lake public trust resources including air and water quality, food and nesting habitat for migratory birds, as well as the recreational opportunities and scenic views that attract many visitors to the Mono Basin. Given the difficulty of forecasting long-term hydrology, D-1631 included a provision requiring the SWRCB to hold a hearing to determine if the 6,391 ft lake level was not achieved within 20 years, "the SWRCB would hold a hearing to consider the condition of the lake and the surrounding area, and will determine if any further revisions to these licenses are appropriate (California State Water Resources Control Board, 1994)."

Since 1994, the lake's water level has not reached the transition water level of 6,391 ft (thus, not triggering the post-transition period). The 6,391 ft transition level has not been reached despite LADWP following the existing export criteria outlined in D-1631. In 2022, the lake dropped to 6,378 ft, which prompted the MLC, the Mono Lake Kootzaduka'a Tribe, CDFW, and Great Basin Unified Air Pollution Control District (GBUAPCD) to ask the SWRCB to take immediate action to prevent further lake declines. The Mono Basin received above average precipitation in water year 2022-2023, which raised the lake to roughly 6,383 ft, but this is still eight ft below the transition water level.

In 2023, recognizing advancements in technology and the possible importance of representing climate change, the SWRCB contracted the UCLA CCS to develop a water budget model of the Mono Basin capable of evaluating various export criteria under past and future climate conditions. The SWRCB selected UCLA CCS for its expertise in climate and water resource modeling, particularly its ability to generate advanced climate projections. Most notably, UCLA CCS has played a significant role in producing datasets for California's 5th Climate Assessment (CA5), supporting more accurate statewide evaluations of climate-driven changes in precipitation, streamflow and extreme weather events. These capabilities are critical for assessing how shifting hydroclimate conditions may affect the Mono Basin and Mono Lake water level.

1.2 Mono Lake Modeling

UCLA CCS performed a thorough literature review to evaluate and inform the approach and methodology for developing the UCLA-MLM. UCLA CCS additionally engaged with and incorporated feedback from technical experts that have been studying the Mono Basin for decades. A review of existing efforts identified four existing Mono Lake water models.

The two primary models, *A Water Balance Forecast Model for the Mono Lake* (known as the Vorster model) and the *Enhanced Stream Analysis Model* (eSTREAM), estimate water levels based on weather and land surface conditions and various diversion scenarios. A third more simplified model developed by the CDFW simulates Mono Lake water level based on changes in storage without considering components such as runoff and precipitation. Recently, a University of Michigan research group developed a fourth Mono Lake model to improve estimates of the natural components influencing the lake's water budget. While documentation was limited at the time of this report, the University of Michigan model aims to

provide a more robust representation of how internal variability may have affected past water levels. All four models are focused on observed weather conditions and how variations in observed weather can influence Mono Lake water level. None were explicitly developed to simulate and evaluate Mono Lake water level in the context of climate change. The two primary models – Vorster and eSTREAM – are described below.

1.2.1 Overview of Vorster Model

The Vorster model is an annual water budget model designed to simulate and forecast Mono Lake water level. Originally developed as a part of Peter Vorster's 1985 thesis (Vorster, 1985), the model has been maintained and updated by MLC in coordination with Vorster (Mono Lake Committee, 2024). It remains a widely used tool for calculating Mono Lake levels with existing and alternative export criteria and for analyzing Mono Lake's hydrology.

The Vorster model includes 18 water budget components to calculate Mono Lake storage change and thus its lake level. Major components include Mono Lake precipitation and evaporation and runoff from surrounding mountains. In the Vorster model, most water budget components fluctuate annually, with variations in areas without direct measurements based on variations measured in proxy locations. To represent the annual variability for portions of the Mono Basin without direct measurements, proxy or "index" measurements from nearby locations inside and outside the Mono Basin are used. These proxies estimate key components of the lake's water budget, including precipitation on Mono Lake's surface, ungauged runoff, and Mono Lake evaporation. The accuracy of the variability of those components depends on how well atmospheric and hydrologic patterns for the proxy region reflect actual conditions over the full spatial extent of those water budget components.

Despite limitations introduced via the use of proxy measurements, the Vorster model provides a detailed representation of the Mono Basin hydrology based on available observations. It allows for flexible diversion scenarios and historical reconstructions using the wrapped-run approach, a method commonly used by LADWP and MLC (described in **Appendix A.5**).

Because the Vorster model is based on historical observations, its ability to simulate climate change impacts is limited. The Vorster model's ability to assess future Mono Lake conditions under climate change has not yet been tested, and would likely prove challenging, requiring the evaluation of projections for all 18 model components.

1.2.2 Overview of eSTREAM Model

eSTREAM was developed in 2011 by Watercourse Engineering in collaboration with LADWP (Watercourse Engineering, 2020), (Los Angeles Department of Water and Power, 2022), to provide a detailed representation of the Mono Basin operations. eSTREAM assesses the ability of LADWP's operations to meet instream flow requirements (IFRs), including stream ecosystem flow (SEF) requirements from the Synthesis of Instream Flow Recommendations (McBain & Trush, Inc. and Ross Taylor and Associates, 2010) and adopted in the Amended Licenses (Los Angeles Department of Water and Power, 2022). Unlike the Vorster model, which represents Mono Lake as a water budget, eSTREAM relies on a multiple linear regression to

estimate monthly changes in Mono Lake storage (and thus water level) using a subset of key water budget components as the independent variables. The terms used in the *e*STREAM regression include Cain Ranch precipitation, Mono Basin runoff from Lee Vining, Walker, Parker, and Rush Creeks, regulated flow released to Mono Lake from these creeks, and Mono Lake's adjusted surface area. These variables estimate Mono Lake water level, and in turn inform operations affecting Mono Lake inflows.

While *e*STREAM can effectively simulate observed conditions and can evaluate existing or alternative export criteria, its reliance on statistical methods limits its accuracy for projecting conditions that fall outside observed conditions, such as unique climate scenarios. The *e*STREAM model also has limitations as it excludes factors like Mono Lake evaporation and ungauged runoff. Furthermore, Sierra Nevada runoff may be given greater weight since both natural and regulated flows are included as independent variables in the model's primary equation. Lastly, despite its detailed representation of LADWP operations, *e*STREAM has limited flexibility in defining diversion scenarios that include more than two phases or shifts in export criteria.

1.2.3 Need for the UCLA-MLM

As previously discussed, neither the Vorster nor *e*STREAM models were explicitly developed to represent and evaluate Mono Lake water level in the context of climate change. The UCLA-MLM was developed to fill this knowledge gap and evaluate if and how climate change already has and may continue to influence Mono Lake's water level. After reviewing existing research and consulting Mono Basin experts, UCLA CCS selected a water budget approach to model storage and water level changes in Mono Lake instead of a statistical method (like the multiple linear regression model used by *e*STREAM). This decision was made because a water budget model is process-based, meaning it accounts for physical atmospheric and hydrological processes that drive changes in Mono Lake rather than relying on correlations from past data. This approach enhances general interpretability, making it easier to understand how different factors influence the lake level. Additionally, a process-based water budget model allows for the evaluation of unprecedented conditions, such as future climate scenarios, better than a purely statistical model. Statistical models can introduce inaccuracies when predicting conditions outside the range their training dataset provides and may therefore struggle to extrapolate beyond historical variations. By representing natural processes and how they are expected to change throughout the entirety of the Mono Basin, a process-based water budget approach can represent both wetting and drying trends in future conditions that may occur due to climate change. This avoids potential biases that could occur in a purely statistics-based model that relies on a limited number of independent variables trained on an observed range of conditions.

1.3 UCLA-MLM Overview

This report provides a detailed description of the development of UCLA-MLM and its use in evaluating Mono Lake conditions in the context of climate change and LADWP exports. This section presents a brief overview of UCLA-MLM and the various processes and datasets used

to simulate Mono Lake's water level. In-depth descriptions of the water budget model and climate change simulations are available in **Section 2** and **Section 3**, respectively. Readers interested in the UCLA-MLM's water level results can proceed to **Section 4**.

UCLA-MLM is comprised of two key parts: climate data representing weather conditions across the Mono Basin and the Mono Lake Water Budget (MLWB), which is a water budget model that uses the climate data to represent the total amount of water entering and leaving Mono Lake.

The MLWB is a process-based model, meaning that it simulates each part of the hydrologic cycle, or the natural processes that move water through the Mono Basin, like precipitation, runoff and evaporation. In addition to these natural components, Mono Lake is also impacted by human decisions and infrastructure, which make up the managed aspects of the system. This includes LADWP exports as well as other operations that impact various streams that feed into the lake, all of which are incorporated into the MLWB.

The primary natural components that impact Mono Lake's water budget, and that are needed to simulate Mono Lake levels using the MLWB, depend on atmospheric and hydrologic conditions across the Mono Basin. These can be simulated using climate datasets which describe weather conditions over a long period of time, using variables like temperature, relative humidity, precipitation totals, etc. While climate data can be produced using observations, or real-world data, observations across the Mono Basin are very limited. Therefore, the climate datasets used in this study were produced using climate models, which are refined using observations and provide a more complete representation of the Mono Basin's climate.

UCLA-MLM allows for analysis of historic Mono Lake conditions as well as projected future conditions, requiring the use of multiple climate model datasets to represent both periods. The ERA5 reanalysis dataset is used to represent modeled observations, or past conditions as they occurred. A set of global climate models (GCMs) from the Coupled Model Intercomparison Project 6 (CMIP6) is used to produce historical simulations, representing climate conditions under historical emissions and future projections, representing climate conditions under future emissions.

A visual overview of the workflow used by UCLA-MLM to model Mono Lake's water level is shown in **Figure 1-5**. UCLA-MLM simulates changes in Mono Lake's water level on an annual timescale, outputting the predicted lake level for April 1st of each year. April 1st is significant because it marks the start of the basin's runoff year and establishes the export limits permitted by LADWP for that year. To calculate this change, atmospheric and hydrologic data describing the Mono Basin's hydrologic cycle are input into the MLWB and used to derive the components of the water budget equation. This hydrology cycle data is derived from global climate data, which is first converted into regional climate data over the Mono Basin using a process called regional downscaling and then run through a hydrologic model.

Figure 1-5

Overview of the UCLA-MLM workflow used to simulate Mono Lake's water level.
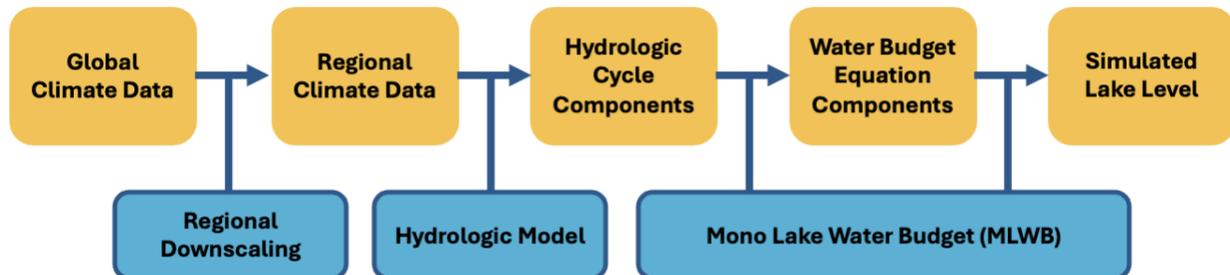
1.3.1 Overview of Global Climate Data

The global climate datasets used in this study are described here. These global climate datasets are subsequently downscaled to produce regional climate data across the Mono Basin as briefly described in **Section 1.3.2** and further described in **Section 2**.

Modeled Observations. Spatially and temporally complete observed data required to represent Mono Lake's water budget is limited. For example, measurements of precipitation have large gaps in their spatial coverage because data is only collected at certain point locations. This study overcomes this limitation by using modeled observations based on the ERA5 reanalysis dataset. The term *reanalysis* refers to a scientific method for reconstructing observed climate conditions using a modeling framework to produce a consistent and comprehensive atmospheric dataset. Climate models divide up sections of the earth into grid cells to output data that is geographically uniform. ERA5 combines observations with global weather models to produce an atmospheric dataset that matches observed weather conditions but with the gridded spatial structure of a model dataset. This gridded format provides complete spatial and temporal coverage of historic conditions as they actually occurred.

Future Projections. The future projected conditions used in UCLA-MLM were derived from Global Climate Models (GCMs), which simulate the Earth's climate system by mathematically representing its components (the atmosphere, oceans, land surface, ice, etc.) and their interactions. These simulations can be carried out with different amounts of atmospheric greenhouse gasses—along with other human-induced changes to the climate system—to simulate how these changes may alter future climate conditions.

In this study, future conditions for the period between 2015 and 2100 are represented using a total of 33 different climate model projections. This includes projections from 11 different GCMs and three SSPs. This ensemble of projected future conditions captures a comprehensive range of potential climate outcomes, which is critical to carrying out a robust climate change analysis. The GCMs were chosen based on their ability to represent California's climate as further described in **Section 3.1.1**. As described in **Section 3.1.2**, the

SSPs include an intermediate (SSP2-4.5), an intermediate-high (SSP3-7.0), and a worst-case (SSP5-8.5) emission scenario. Each projection in the ensemble is considered plausible and therefore plays an important role in determining the overall likelihood of Mono Lake recovery and supporting informed decision making.

Historical Simulations. The same GCM ensemble used to project future conditions can also be used to represent historical climate conditions. During these historical simulations, GCMs are run for the period between 1955 to 2014 using historically observed emissions. By producing multiple reconstructions of historical conditions, the use of historical simulations can provide greater insight into past climate change impacts compared to observations alone. In this study, an ensemble of 11 GCMs is used to simulate historic Mono Basin conditions and assess climate change impacts during the historic period. It is important to note that all historical simulations use the same emissions scenario, so prior to 2015, there is no difference between the three SSPs.

1.3.2 Extraction of Hydrologic Cycle Components

The modeled observations, future projections, and historical simulations include the fundamental climate variables that drive the hydrologic cycle in the Mono Basin. However, to translate these climate datasets into the individual hydrologic components needed to represent Mono Lake's water budget, several additional steps are required (**Figure 1-6**).

Regional Downscaling. GCM outputs and ERA5 reanalysis are both global datasets which characterize climate conditions across the entire Earth and are not designed to represent climate conditions at the regional level. Before global datasets can be used to simulate weather across the Mono Basin, they must first undergo a process called *regional downscaling*, which turns low-resolution global data into high-resolution regional data. Global datasets have coarse spatial coverage, meaning that each grid box encompasses a large geographic area. Because of this, global data is unable to capture important geographic variations in weather and climate over the Mono Basin. Downscaling is therefore carried out to simulate Mono Basin conditions at scales fine enough to accurately reproduce the natural processes that influence Mono Lake's water budget.

Both the ERA5 dataset and the GCM projections are downscaled to the same 3 km x 3 km grid shown in **Figure 2-2**. The ERA5 data is downscaled using the Weather Research Forecasting Model (WRF) and the GCMs were downscaled as part of CA5 using the Hybrid Localized Constructed Analogs version 2 (LOCA2-Hybrid) method.

Hydrologic Modeling. While some components of the water budget can be extracted directly from this downscaled climate dataset, like precipitation and evaporation, a hydrologic model is necessary to represent components impacted by land surface conditions, like runoff. To simulate Mono Basin runoff, the downscaled data is input into a version of Noah-Multiparameterization (Noah-MP) hydrologic model specifically calibrated to represent natural runoff across California.

These processing steps prepare the data for use in the MLWB and are carried out for both the GCM projections and the historic ERA5 data. The resulting atmospheric and hydrologic data allow for the extraction of all components of the hydrologic cycle needed to represent Mono Lake's water budget and calculate annual change in Mono Lake storage within UCLA-MLM.

Figure 1-6

Overview of the processes used to extract key components of the Mono Basin's hydrologic cycle from global climate data.
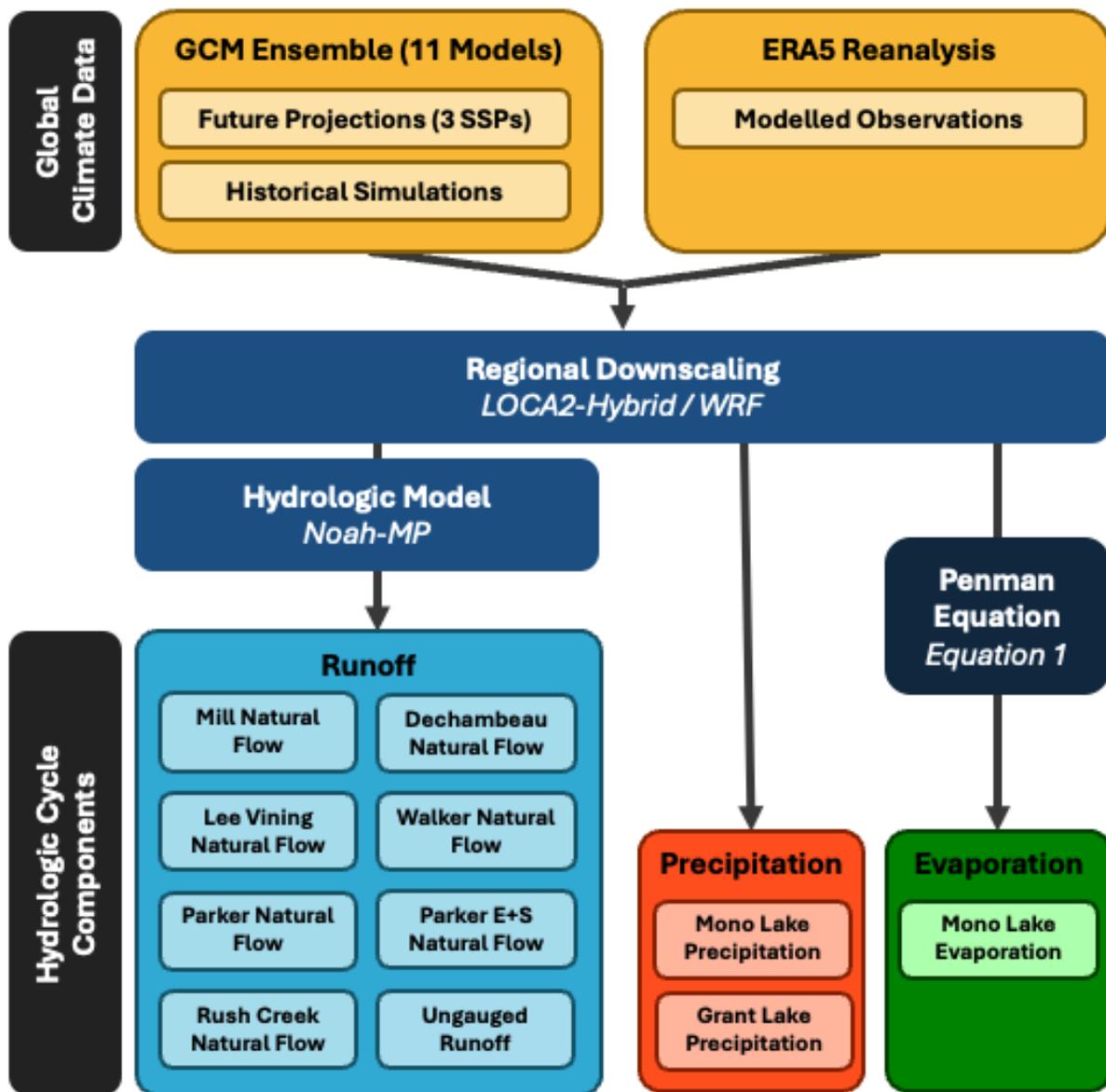
2 DEVELOPMENT OF THE MONO LAKE WATER BUDGET

UCLA CCS developed a physics-based water budget model—called the Mono Lake Water Budget (MLWB)—to simulate natural hydrologic processes (e.g., precipitation, runoff, evaporation) across the Mono Basin and the lake's resulting storage and water level. The MLWB was developed using high-resolution atmospheric and hydrology datasets from CA5 (Bass et al., 2023; Pierce et al., 2023), known as ERA5-WRF, which represent the basin's modeled observations.

The basin's modeled observations are used in the MLWB to estimate Mono Lake water level and validate the MLWB. Modeled observations are valuable because they can be compared against observed data. This is not only beneficial for describing historical conditions, but also future conditions, because future climate projections (discussed in **Section 3**) are bias corrected to these modeled observations. The validation provided in this section compares ERA5-WRF data to station observations of precipitation, runoff, and lake level across the Mono Basin. For components lacking a long-term record of direct measurements—such as evaporation and ungauged runoff—parameter values were adjusted to align the simulated lake level with the observed lake level (outlined in Appendix A.2.3). This step is essential for building confidence in the UCLA-MLM's ability to simulate how hydroclimate changes affect Mono Lake's water level—both historically and under future projections.

The MLWB was developed following the workflow shown in **Figure 2-1**. The ERA5-WRF atmospheric data is developed and then used as a forcing for a hydrologic model to obtain the hydrologic variables needed for the MLWB. **Section 2.1** describes this process, including the development of the ERA5-WRF dataset and the validation of the key atmospheric and hydrologic variables. Modeled observations of precipitation and runoff are then extracted from the ERA5-WRF grid (**Figure 2-2**) for use in the MLWB. **Section 2.2** provides a detailed description of the MLWB and the mass balance equation used to characterize Mono Lake's inflows and outflows. A final evaluation is performed in **Section 2.2.3** to assess the MLWB's ability to reproduce Mono Lake's observed water level.

While this section presents a general overview of the ERA5-WRF data and the MLWB in a manner suitable for a broad audience, **Appendix A** is referred to throughout these sections and includes additional technical details that are relevant to the UCLA-MLM development. While relevant, these technical details are provided in **Appendix A** to avoid detracting from the broader conceptual understanding of the MLWB in the main report. The evaluation of ERA5-WRF presented in this report focusses specifically on performance in the Mono Basin, however, additional details on ERA5-WRF's development and statewide validation are available in CA5 technical summaries (Bass et al. 2023; Pierce et al. 2023).

Figure 2-1

Overview of the workflow used to set-up the Mono Lake Water Budget (MLWB).
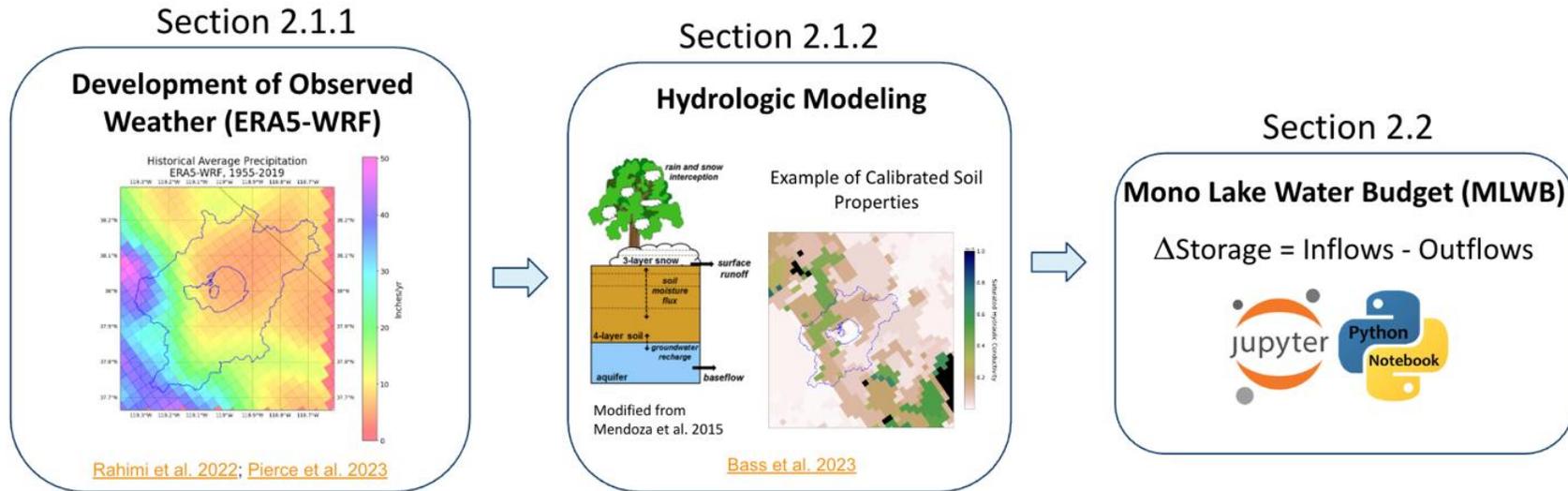
Figure 2-2

*The core Mono Basin components used to develop the UCLA-MLM water budget. For reference, the grid represents the 3x3 km resolution of the ERA5-WRF dataset (modeled observations). Basins with colors and labels contain measured data used for validation of modeled observations of natural flow for Lee Vining, Walker, Parker, and Rush Creeks. The outline of Mono Lake (blue line), and the resulting ungauged runoff area (black line), vary depending on Mono Lake's storage changes, and thus changes in its surface area. Diversions (grey dashed line) includes approximate location of Lee Vining Conduit and the Mono Craters Tunnel. Light blue lines represent prominent (stream order at least equal to three) rivers and their tributaries in the Mono Basin, with Owens River additionally shown for reference. Note, the same grid or resolution is used for the climate projections later discussed in **Section 3**.*
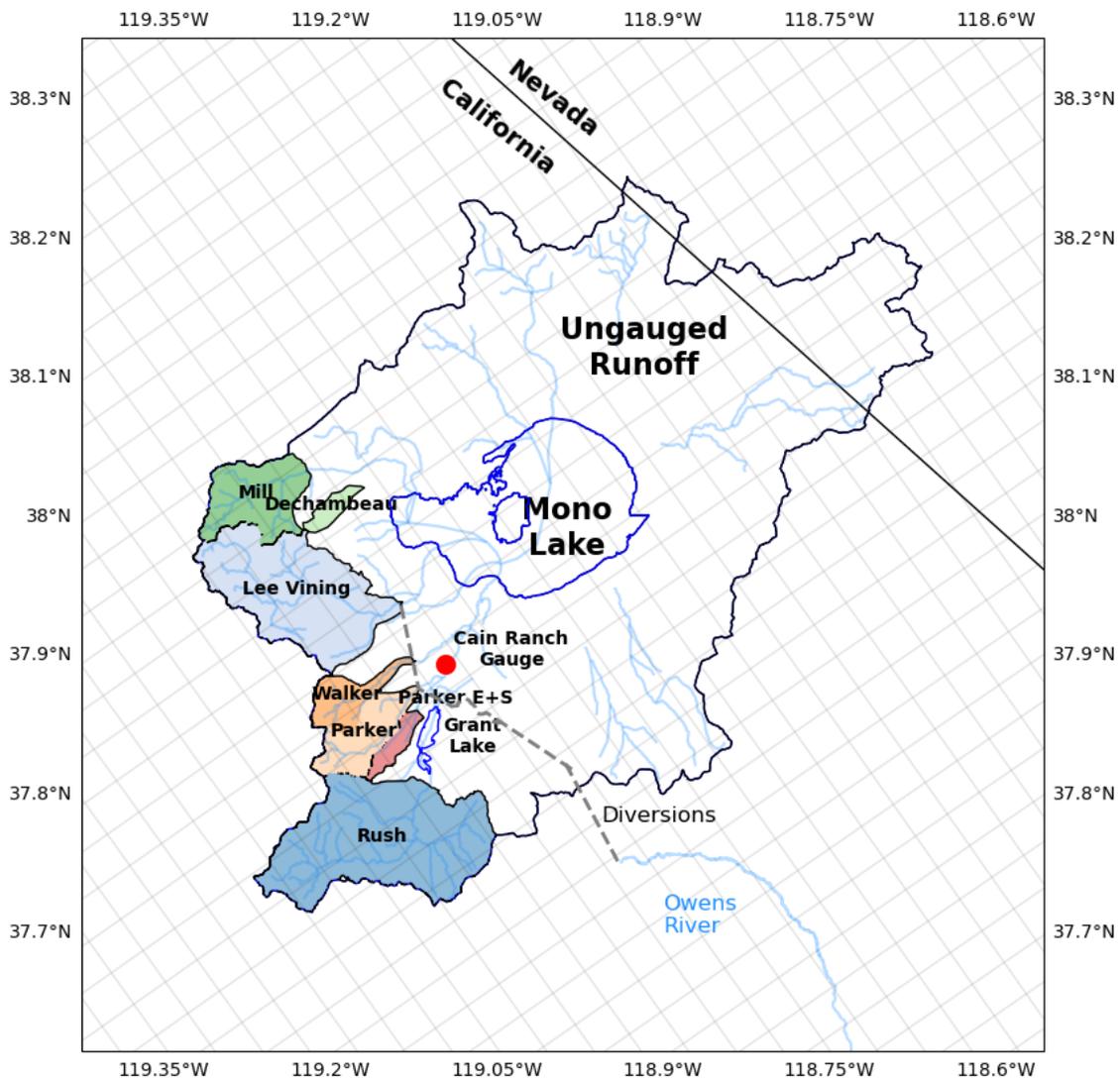
2.1 Modeled Observations of Mono Basin Conditions

To represent observed atmospheric and hydrology conditions across the Mono Basin, UCLA CCS developed a 3 km x 3 km spatially gridded hydroclimate dataset by combining reanalysis data with downscaling techniques. Specifically, the fifth-generation reanalysis dataset (ERA5) produced by the European Centre for Medium-Range Weather Forecasts (ECMWF) (Hersbach, 2020) was combined with the Weather Research Forecasting regional climate model (WRF), to produce the hydroclimate dataset collectively referred to as ERA5-WRF. This hydroclimate dataset spans the period from January 1st, 1951, to December 31st, 2020 for atmospheric variables. The development of ERA5-WRF, along with its bias correction to station data across California, was performed for CA5 and is outlined in Rahimi et al. 2022 and Pierce et al. 2023. A detailed description of ERA5-WRF is available in the aforementioned references, while a validation of the ERA5-WRF dataset relevant to the Mono Basin is provided in this section.

Since additional Mono Basin data was made available after the development of ERA5-WRF for CA5, additional adjustments to the ERA5-WRF data, including mean-state adjustments of its precipitation and runoff, were applied to improve ERA5-WRF accuracy in the Mono Basin. The technical details associated with these adjustments are outlined in **Appendix A.1**, with the validation of the modeled observations provided in the main report. Unless otherwise noted, all subsequent references to ERA5-WRF in this report include the Mono Basin specific adjustments that were applied.

2.1.1 Evaluation of ERA5-WRF Atmospheric Data

This section provides an overview of the ERA5-WRF atmospheric data used in the UCLA-MLM. This includes precipitation over Mono Lake, which has a nearby station to compare against, and evaporation from Mono Lake which does not have nearby observations to compare against. These variables are the key atmospheric components of the MLWB.

Figure 2-3

Spatial representation of the 1955-2019 average annual precipitation from modeled observations (ERA5-WRF) across the Mono Basin. Data incorporates Cain Ranch adjustment (as outlined in Appendix A.1). For the MLWB (discussed in Section 2.2), this adjustment only impacts Mono Lake precipitation.
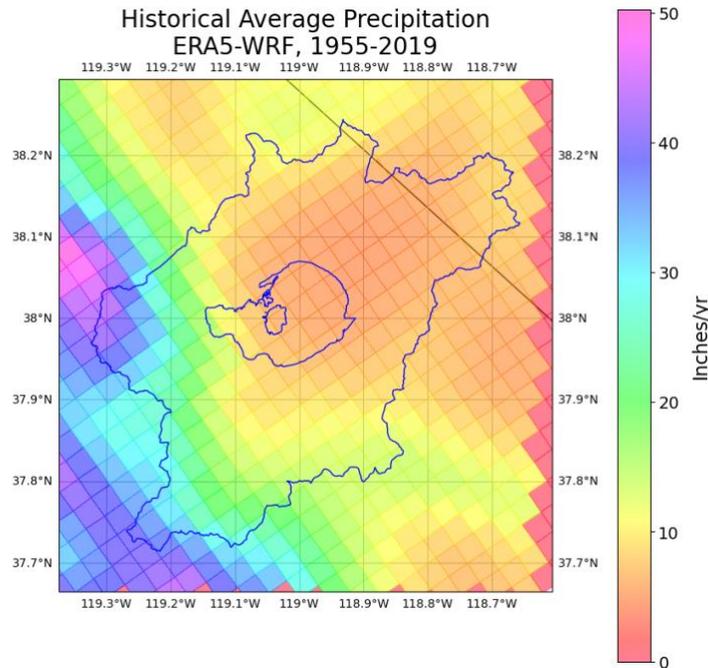
Precipitation. **Figure 2-3** shows the modeled observational average precipitation across the Mono Basin. Importantly, this figure demonstrates the ability of ERA5-WRF to capture small-scale spatial patterns of precipitation known to exist throughout the Mono Basin (Vorster, 1985). For example, higher precipitation is captured along the western edge of the Mono Basin, where the high elevation Sierra Nevada mountains are located. Precipitation values to the east of Mono Lake are shown to be relatively lower, as expected (Vorster, 1985).

The ERA5-WRF dataset was also evaluated for its ability to capture year-to-year variability and long-term trends at Cain Ranch, the most reliable and long-term station in the Mono Basin near Mono Lake. The location of the Cain Ranch station is shown in **Figure 2-2**. Generally, the spatial representation of precipitation across the Mono Basin (**Figure 2-3**), and the year-to-year variability and long-term trends at the Cain Ranch station are well captured by ERA5-WRF (**Figure 2-4**). Collectively, this builds confidence in the modeled observations and its ability to produce data across the Mono Basin that is complete and physically realistic.

Figure 2-4

*a) Modeled observation (ERA5-WRF, red line) of annual Cain Ranch precipitation compared to observed station data (black line). The inter-annual variability in precipitation is accurately represented, providing confidence in ERA5-WRF's ability to represent precipitation. **b)** Long-term trend of ERA5-WRF and observed precipitation at Cain Ranch based on a 30-year rolling average (e.g. 1985 represents precipitation from 1956 to 1985). As shown, ERA5-WRF accurately represent the long-term observed trend.*
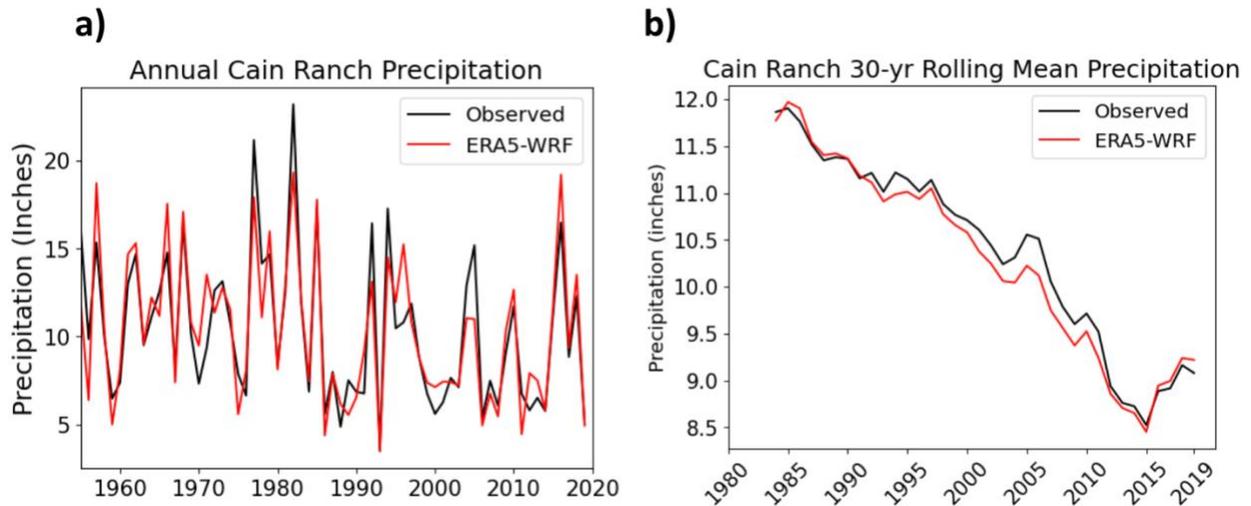
While precipitation observations directly over Mono Lake are not available, this term is necessary for Mono Lake's water budget, which is later discussed in **Section 2.2**. The lack of observed precipitation on Mono Lake highlights the usefulness of a spatially complete hydroclimate dataset like ERA5-WRF, which is able to represent precipitation on Mono Lake. The precipitation over Mono Lake was based on the average precipitation across the ERA5-WRF grid cells that fall within Mono Lake (**Figure 2-2**). The spatially averaged value from these grid cells, expressed as a depth of precipitation in ft, was then multiplied by Mono Lake's surface area (acres) for a given runoff year to obtain the total annual precipitation over Mono Lake (ac-ft/yr). Simulated Mono Lake precipitation is roughly 3 to 4 inches less than observations at Cain Ranch (shown in **Figure A-4**), which is expected due to Mono Lake's lower elevation, resulting in weaker orographic enhancement, and its more easterly location within the rain shadow.

Evaporation. Since Mono Lake is a terminal lake, evaporation is its primary natural loss mechanism, making it an important component of the water budget. Although long-term evaporation measurements from Mono Lake are unavailable, the ERA5-WRF dataset includes all necessary meteorological variables to estimate lake evaporation using the widely accepted Penman equation (Penman, 1948). The equation estimates evaporation from an open body of

water using meteorological conditions such as vapor pressure deficit, solar radiation, wind speed, and temperature:

Equation 1.

$$Evaporation = \frac{(\Delta * R_n) + \left(\rho * c_p * \frac{VPD}{r_a}\right)}{\lambda_v * (\Delta + \gamma)}$$

In **Appendix A.1**, more details are provided regarding each term in this equation. Evaporation from Mono Lake was calculated based on the average evaporation across the Mono Lake grid cells shown in **Figure 2-2**. Like precipitation, this provides a depth which is later converted to a volume of water based on the average surface area of Mono Lake for a given runoff year. A mean-state adjustment of ERA5-WRF evaporation was performed during the development of the MLWB (described in **Appendix A.2.3**), which led to a historical average of 47.25 in/yr. The year-to-year variability of evaporation is shown in **Figure 2-5**. The average evaporation aligns closely with the average evaporation used by Vorster, another process-based water budget model (1985).

While the Penman equation provides the annual evaporation based on freshwater, the actual amount of evaporation can vary year to year based on the salinity of Mono Lake. As elevation decreases, salinity increases, leading to a reduction in evaporation. The UCLA-MLM applied a simplified relationship to represent this effect: a maximum evaporation reduction of 7% occurs at 6,360 ft and decreases linearly to 3% at 6,405 ft. Above 6,405 ft, the 3% reduction remains constant, and below 6,360 ft the 7% reduction remains constant (**Figure 2-6**). This approach reflects the method used by the Vorster model (Vorster 1985, Mono Lake Committee 2024).

Figure 2-5.

Estimated annual Mono Lake evaporation from 1955-2020. Figure is based on the Penman equation, with a mean-state adjustment applied to ensure accurate representation of Mono Lake's water budget. Salinity is considered in the MLWB but not accounted for in this figure since it depends on Mono Lake's water level.
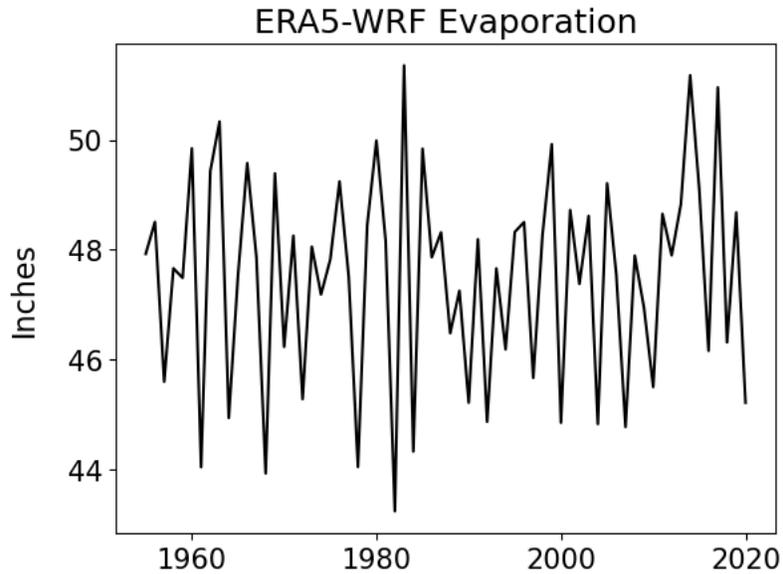

Figure 2-6.

Estimated effect of salinity on evaporation diminishes as Mono Lake elevation rises. The curve shows a linear decline in evaporation reduction from 7% to 3% between elevations of 6,360 ft and 6,405 ft, with a constant 3% reduction above 6,405 ft and a constant 7% reduction below 6,360 ft.
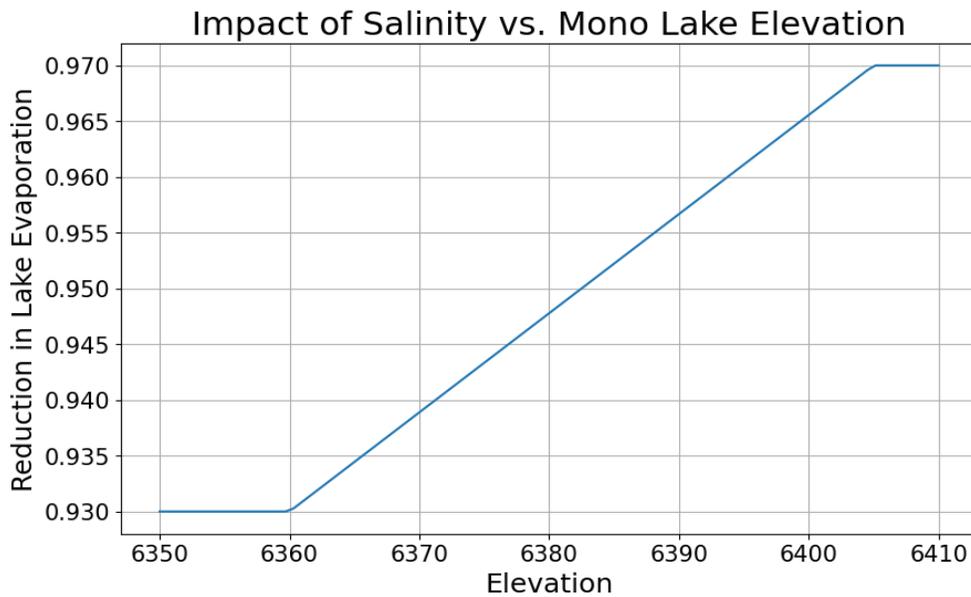
2.1.2 Evaluation of ERA5-WRF Hydrology Data

ERA5-WRF provides atmospheric variables at the ground surface (e.g., precipitation and air temperature) and serves as forcing inputs to a hydrology model. In this context, *forcing* means the weather and climate variables supplied to the hydrology model that are required to "force" the land surface response from the hydrology model. The hydrology model estimates how terrestrial water processes (e.g. runoff or natural flow) that occur at the land surface respond to the atmospheric or forcing variables. A hydrology model is thus needed to represent a spatially complete water budget of Mono Lake, since the flow into Mono Lake serves as a critical component of the MLWB later discussed in **Section 2**. As a part of CA5, a hydrology model called Noah-Multiparameterization (Noah-MP) within the WRF-Hydro platform (Gochis et al. 2020) was set-up and calibrated to represent natural flow across California. Noah-MP receives ERA5-WRF atmospheric variables as its forcing dataset and solves for snowpack, surface and subsurface runoff, infiltration, evapotranspiration, and additional variables. The modeled observations of atmospheric and hydrologic conditions are collectively referred to as ERA5-WRF throughout this report.

Details regarding the hydrology model set-up, calibration, evaluation, and simulations, which were performed for CA5, can be found in Bass et al. 2023. Similar to the observed precipitation data, additional observations of natural flow data were obtained after the hydrology simulations were performed for CA5. As such, a mean-state adjustment was applied to the simulated natural flow based on comparisons to observed Mono Basin natural flow data obtained from LADWP during this project. Details regarding this adjustment are outlined in **Appendix A.1**. This correction refined the hydrologically modeled natural flow from the four major Sierra Nevada tributaries that flow into Mono Lake to better align with observations (**Figure 2-7**), while other creeks were adjusted based on their conversion from natural flow to observations of regulated flow (described in **Appendix A.2.1**).

To obtain the natural flow from each creek in units of ac-ft, the spatially averaged depth of runoff from ERA5-WRF hydrology across each subbasin (ft), as shown in **Figure 2-2**, was multiplied by the subbasin's drainage area (in acres, **Table 2-1**).

Table 2-1.

Drainage area of basins represented in the Mono Basin. Ungauged drainage area is shown for a Mono Lake water level of 6,385 ft; however, the drainage area for ungauged runoff varies depending on Mono Lake's surface area (Figure A-8).

Basin Name	Rush	Lee Vining	Walker	Parker	Mill	Decham-beau	Parker E+S	Ungauged
Area (km²)	132.3	103.7	19.3	28.0	41.8	7.1	8.2	1274.1

In **Figure 2-7**, it is shown that the hydrology model is able to capture the year-to-year variability along the primary Mono Basin creeks. These creeks are commonly referred to as the four-creeks and include Lee Vining, Walker, Parker, and Rush Creeks. The total natural flow from these four creeks is commonly referred to as the four-creek runoff, which influences streamflow requirements and LADWP operations in the Mono Basin (described in **Appendix A.3.2**).

In **Figure 2-8**, it is demonstrated that the four-creek runoff trends from ERA5-WRF accurately reflect observations. This assessment builds confidence in the downscaled and hydrologic modeling data that was produced as a part of CA5 which was further refined for this report.

Figure 2-7.

Modeled observations (ERA5-WRF, red line) of Lee Vining, Walker, Parker, and Rush Creeks (the individual creeks that make up the four-creek runoff in the Mono Basin) as compared to station data (black line). Modeled observation includes a mean-state adjustment which is outlined in Appendix A.1
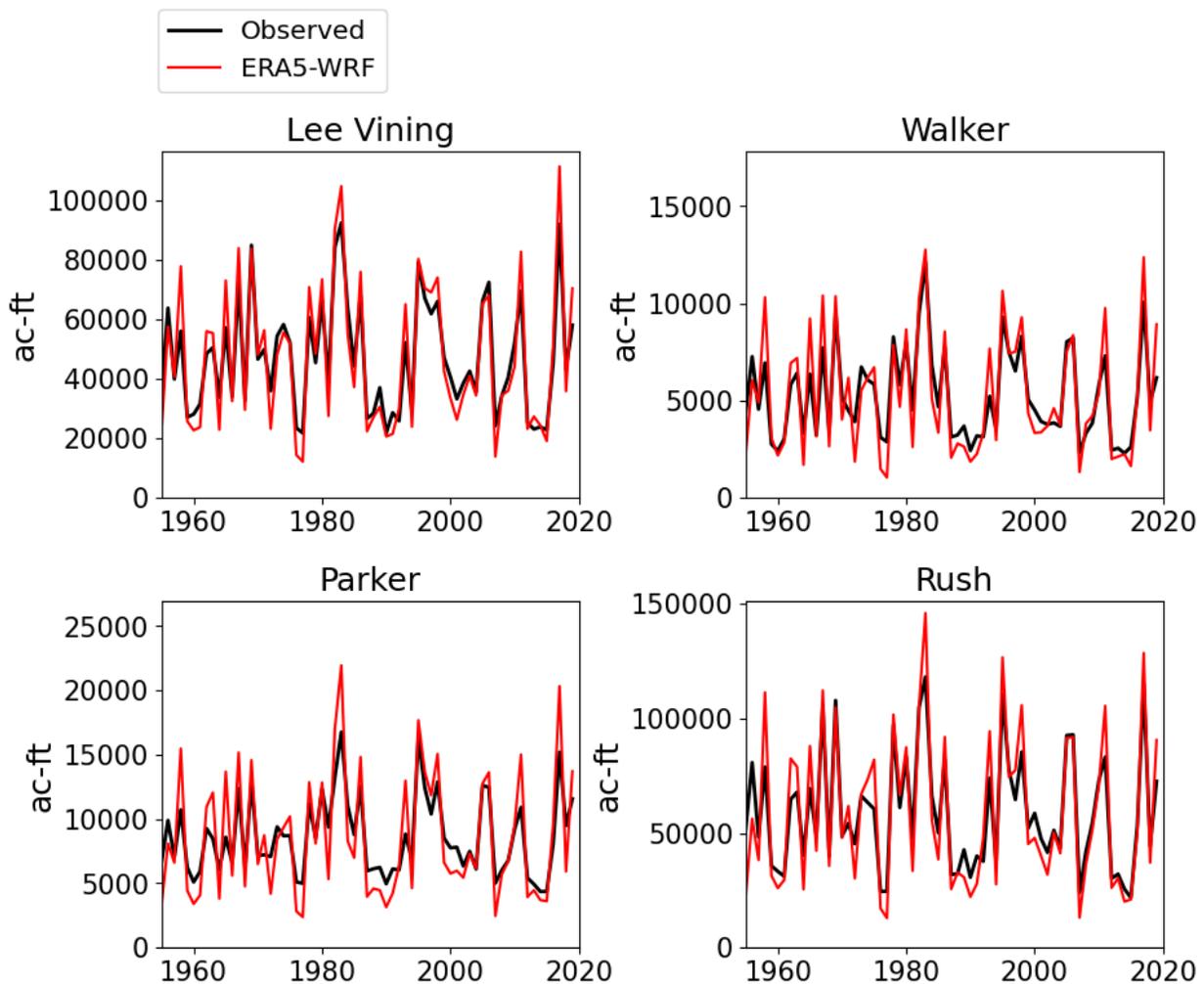
Figure 2-8

Long-term trend of modeled observations (ERA5-WRF, red) and the observed four-creek flow (black) based on a 30-year rolling average (e.g. 1985 represents precipitation from 1956 to 1985).
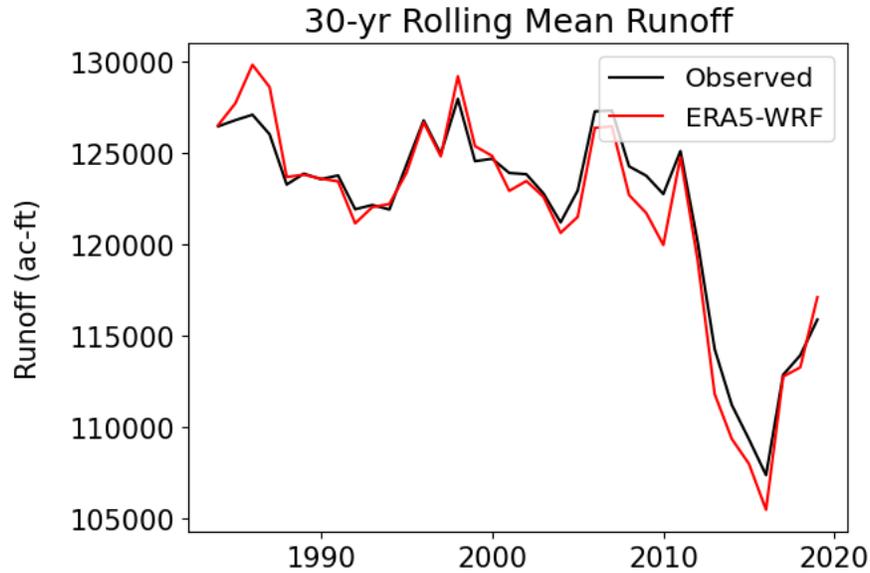
2.2 Mono Lake Water Budget (MLWB)

UCLA CCS derived the MLWB using a mass balance representing inflows to Mono Lake and outflows (or losses) from Mono Lake. The combination of inflows and outflows in a given year represents the total annual change in storage in Mono Lake. The components of Mono Lake inflows and outflow represented in the MLWB are described below. **Figure 2-9** provides an overview of the MLWB and presents a visual representation of the water budget equation described in **Section 2.2.1**.

Figure 2-9.

Visual representation of MLWB showing the individual components of the water budget equation.
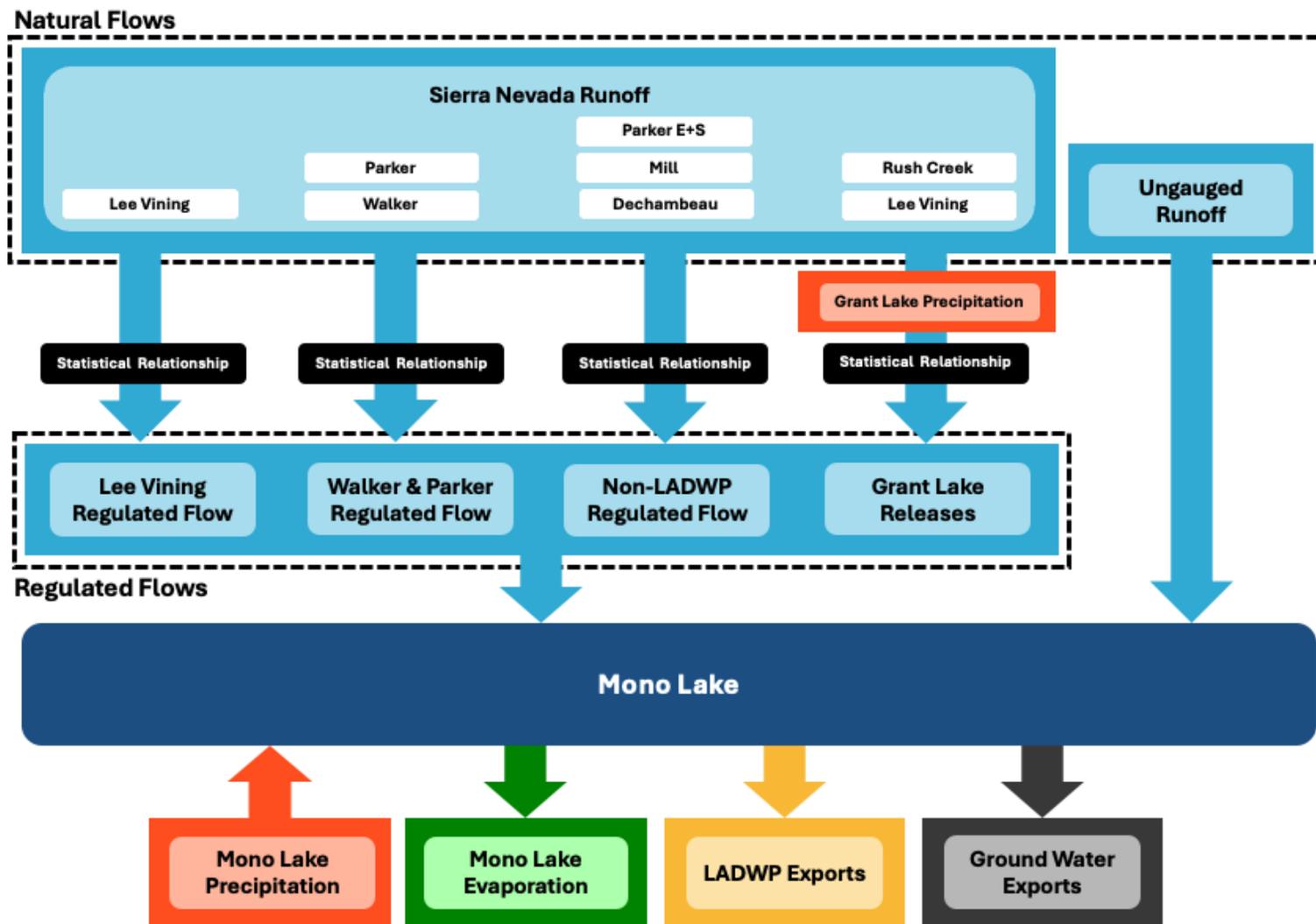
Inflows

1. **Mono Lake Precipitation ($P_{Mono\ Lake}$):** Precipitation that falls directly into Mono Lake.
2. **Surface Flows ($Q_{inflows}$) :** Surface water that flows into the lake from the surrounding area.
    a. **Regulated Flow from Sierra Nevada Runoff:** Streams that feed into Mono Lake which are managed or modified by human operations. These streams originate in set of sub-basins in the Sierra Nevada.
        i. **Lee Vining Regulated Flow ($Q_{Lee\ Vining}$):** Represents flow derived from Lee Vining Natural Flow.
        ii. **Walker and Parker Regulated Flow ($Q_{Walker\ \&\ Parker}$):** Represents flow derived from Walker & Parker Natural Flow.
        iii. **Non-LADWP Regulated Flow ($Q_{Non-LADWP}$):** Represents flow from creeks that are not managed by LADWP out-of-basin diversions, but that may still be altered by hydropower and/or irrigation. Derived from Parker East and South Natural Flow, Mill Natural Flow and DeChambeau Natural Flow.
        iv. **Grant Lake Releases ($Q_{Grant\ Lake\ Release}$):** Represents the total flow released from Grant Lake reservoir, including flow across its spillway and via its outlet. Note, this reservoir is located along Rush Creek. Derived from Lee Vining Natural Flow, Rush Creek Natural Flow and Grant Lake Precipitation.
    b. **Ungauged Runoff ($Q_{Ungauged}$):** Runoff directly into Mono Lake from all other portions of the Mono Basin that are not part of the Sierra Nevada Runoff. The Ungauged Runoff is not modified by human activity and is primarily sourced from small, ungauged sub-basins in the Sierra Nevada and from smaller mountain ranges around Mono Lake **Figure 2-2**.

Outflows

1. **Mono Lake Evaporation ($E_{Mono\ Lake}$):** Evaporation directly from Mono Lake.
2. **LADWP Exports ($Exports$):** Surface water diverted by LADWP, from tributaries that would otherwise naturally flow into Mono Lake. Exports are determined by Export Criteria, which are a set of regulations that dictate the maximum amount that LADWP can export in a given year.
3. **Groundwater Exports ($GW\ Exports$):** Groundwater intercepted in the Mono Craters Tunnel that is sourced from the Mono Basin, that would have flowed toward Mono Lake.

2.2.1 Water Budget Equation

The water budget equation is calculated in units of acre-feet per year (ac-ft/yr):

Equation 2.

$$\Delta Storage = Inflows - Outflows$$

The change in Mono Lake's water storage over the runoff year (April 1 to March 31 of the following year) is added to the lake's initial storage on April 1. This results in the total water volume for that year, which is then converted to a lake level using the volume–elevation relationship shown in **Figure 2-10**.

Figure 2-10.

The MLWB estimates changes in Mono Lake storage across a runoff year. This is added to the previous year's storage to determine the total storage or volume of water in the lake. The relationship shown here is then used to convert Mono Lake storage (volume) to its water level (elevation).
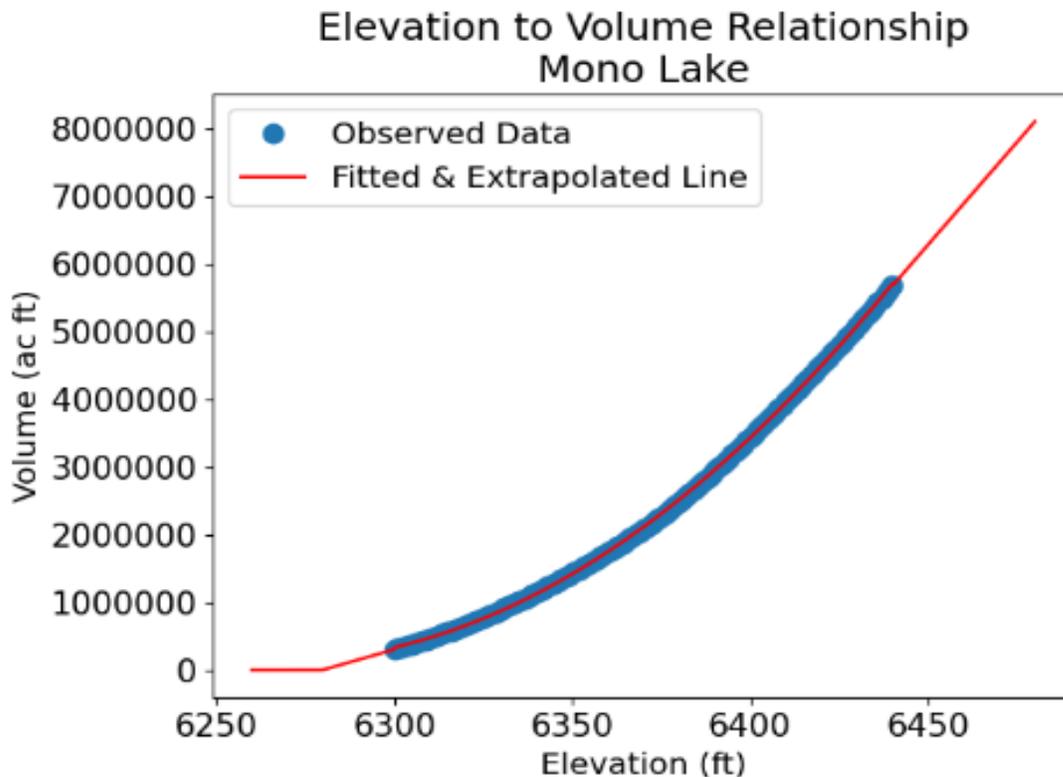
In the MLWB, inflow terms include precipitation on Mono Lake and surface flows, or water that flows into Mono Lake. Outflows include surface water exports from water that is released from Grant Lake and evaporation from Mono Lake. The water budget is shown conceptually in **Figure 1-2b** and is summarized in **Equation 3** below:

Equation 3.

$$\Delta Storage = Q_{inflows} + P_{Mono\ Lake} - E_{Mono\ Lake} - Exports$$

Equation 3 provides a general overview of the MLWB with inflows and outflow broken down into their individual components. However, in practice the equation contains additional details relating to $Q_{inflows}$, groundwater exports ($GW\ Exports$) and an $Error\ Term$. The error term is necessary to more accurately represent changes in storage during dry and wet years, which is outlined in **Appendix A.3.2**. The groundwater export term is necessary to include since the Mono Craters Tunnel, via which surface water exports are made, also intercepts an average amount of roughly 5,500 ac-ft/year of groundwater that is sourced from the Mono Basin (Mono Lake Committee 2022). Variability in this term is not included due to limited understanding and data of the Mono Basin's groundwater spatiotemporal dynamics. The resulting water budget equation (Equation 4) and the expanded form of $Q_{inflows}$ (Equation 5) are outlined below:

Equation 4.

$$\Delta Storage = Q_{inflows} + P_{Mono\ Lake} - E_{Mono\ Lake} - Exports - GW\ Exports$$
$$+/- Error\ Term$$

Equation 5.

$$Q_{inflows} = Q_{Lee\ Vining} + Q_{Walker\ \&\ Parker} + Q_{Grant\ Lake\ Release} + Q_{Non-LADWP}$$
$$+ Q_{Ungauged}$$

2.2.2 Representation of Surface Flow into Mono Lake

A key task in developing the UCLA-MLM involved incorporating runoff from the Sierra Nevada mountains that ultimately reaches Mono Lake. This inflow plays a critical role in determining the lake's storage volume and water level. Previous analysis demonstrated the Noah-MP hydrologic model's ability to represent the natural runoff across the Mono Basin's four major creeks (Lee Vining, Walker, Parker, and Rush; **Figures 2-7, 2-8**). However, before reaching Mono Lake, this natural runoff may be altered by irrigation, hydropower operations, instream flow requirements and water supply diversions.

Aside from the ungauged runoff ($Q_{Ungauged}$) each inflow term is modified from its natural flow conditions. The modified flow is commonly referred to as regulated flow. Accounting for these modifications is necessary to accurately represent Mono Lake's water budget. Here, a brief overview of this process is provided, with further detail provided in **Appendix A.2.1**. The natural flow is translated into regulated flow (the flow after human modifications are taken into account) via a series of statistical relationships based on the relationship between simulated natural flow and observed regulated flow. These relationships were based on data from 1994 to 2019, a period that reflects modern land use practices and operational constraints, such as hydropower production and streamflow requirements.

All regulated flow measurements are sourced from LADWP's database, except for Mill Creek, which is monitored by Southern California Edison and publicly available through United States Geological Survey (USGS) stations (stations outlined in **Appendix A.2.1**). For most creeks, the relationship between natural and regulated flow can be captured using a simple linear regression. The only exception is $Q_{Grant\ Lake\ Release}$ which is subject to more complex flow management tied to reservoir operations at Grant Lake (discussed in **Appendix A.2.1**). **Figure 2-11** demonstrates the relationships used to convert ERA5-WRF natural flow to regulated flow for each term. The simulated regulated flow is derived by applying this statistical relationship to the ERA5-WRF natural flow. The derived ERA5-WRF or simulated representation of regulated flow is compared against the observed regulated flow in **Figure 2-12**. Using this approach, approximately 90% to 94% of the variability in regulated flow into Mono Lake is represented. The strong relationship between natural flow and regulated flow provides confidence in their use for natural flow from other observed time-periods (e.g. **Appendix A.2.5**) and from climate projections (later described in **Section 3**).

Here, a general overview of the ERA5-WRF data and MLWB equation are provided; however, readers interested in additional details regarding the development and quality control testing of the MLWB should reference **Appendix A**. As mentioned previously, the technical details in **Appendix A** include, but are not limited to, how regulated flow is represented for Grant Lake and additional tributaries in the Mono Basin, how instream flow requirements are represented, how modern-day irrigation changes are accounted for, how the average amount of observed evaporation and ungauged runoff were determined, and how the error term is represented.

Figure 2-11

The relationship used to convert modeled observations of natural flow (x-axis) to regulated flow into Mono Lake (y-axis). Relationship is based on data from 1994–2019. A simple linear regression is used to estimate regulated flow for all creeks except Grant Lake Releases, which requires a more complex relationship based on a multiple linear regression detailed in **Appendix A.2.1**. *As a result, a simple linear regression line is not shown for Grant Lake.*
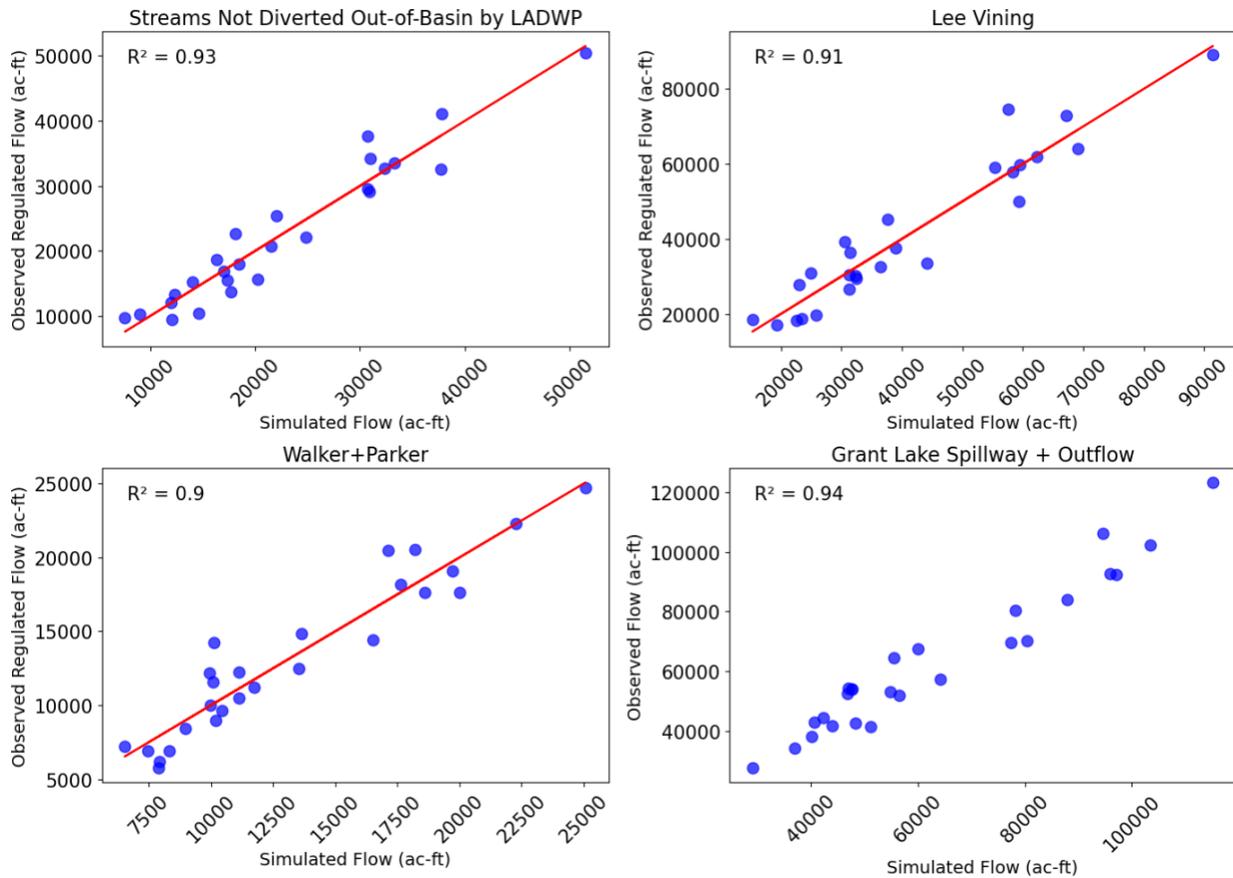
Figure 2-12

Estimated flow into Mono Lake based on the modeled observations of natural flow and its conversion to regulated flow. Modeled observations of regulated flow are shown in red, while observed regulated flow is shown in black.
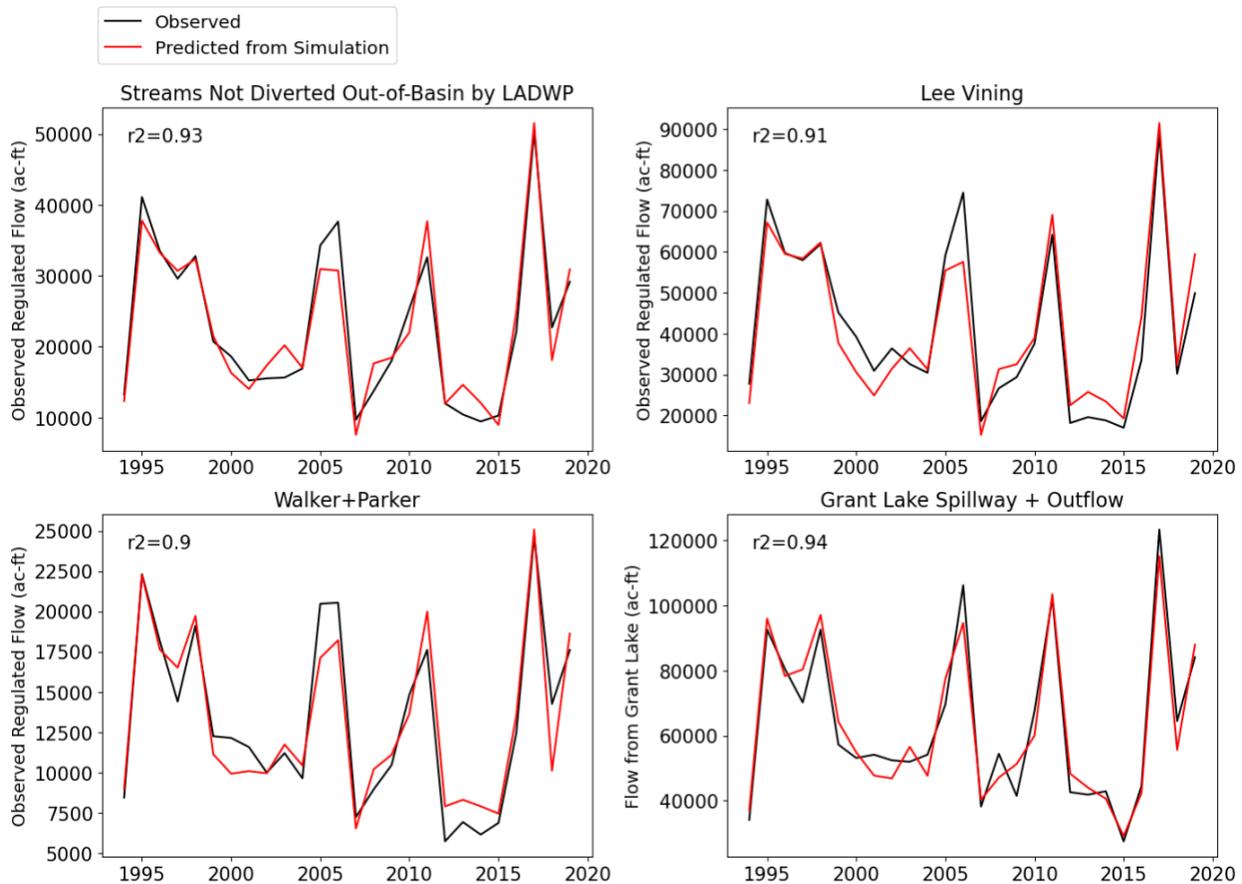
2.2.3 Evaluation of the Mono Lake Water Budget (MLWB)

The UCLA-MLM, which combines atmospheric and hydrologic data (e.g. ERA5-WRF) with the MLWB, was evaluated to assess its ability to reproduce observed Mono Lake water level. By comparing simulated conditions against observed conditions, the MLWB was tested against real-world water level records to evaluate its reliability. The water level assessment shown here was performed for the years 1994 to 2020, a period reflecting recent land use and hydropower conditions. To reflect observed conditions, observed export amounts were applied during this time-period (e.g. shown in **Figure 1-3b**). The resulting MLWB simulated water level is compared to the observed water level in **Figure 2-13**. The simulated water level has a mean error of 0.01 ft, and an absolute mean error of 0.48 ft. While the UCLA-MLM was set-up and evaluated from 1994 to 2020, to reflect recent land use conditions in the Mono Basin, a longer evaluation since

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1971 provides reliable performance as well (**Figure A-12**). The results demonstrate close agreement between simulated and observed data—highlighting the MLWB's reliability for future projections.

Figure 2-13

Simulated water level (red) compared to observed water level (black) for the MLWB.
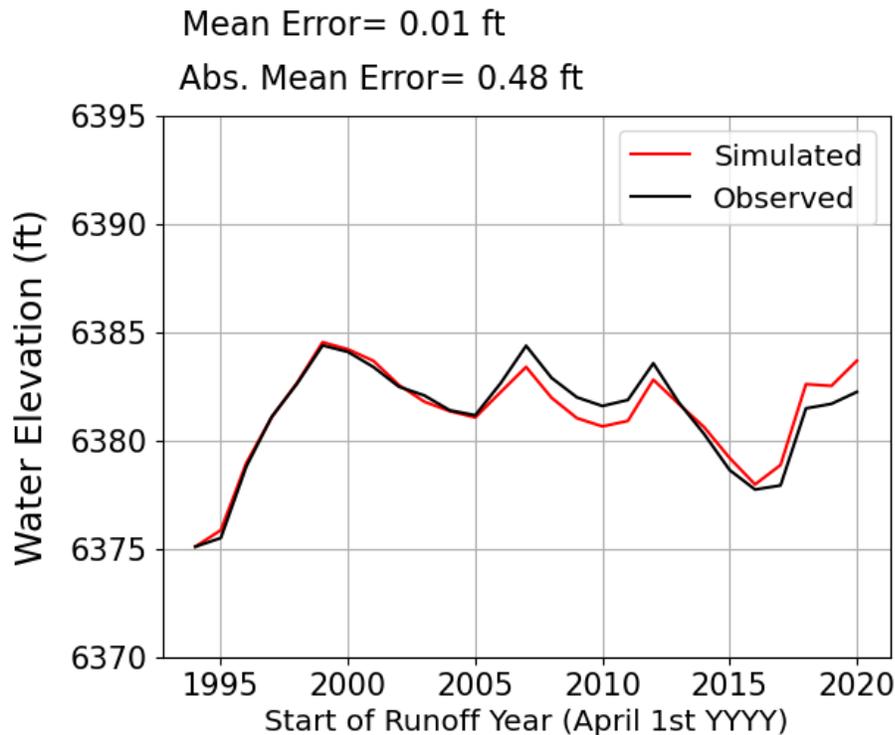
It is also important to note that ERA5-WRF enables an explicit representation of key components in the MLWB equation, such as ungauged runoff, precipitation over Mono Lake, and evaporation from Mono Lake, which are not directly available from observed data. This ability to represent every component in the MLWB and their importance in a process-based manner helps clarify how individual components affect lake conditions. **Figure 2-14** summarizes the long-term historical average contribution of key hydrologic components to Mono Lake's overall water budget. To summarize the components that contribute to Mono Lake's water budget, the following terms are used: Sierra Nevada Runoff, Ungauged Runoff, Mono Lake Precipitation (P), Mono Lake Evaporation (PET), and Exports. Sierra Nevada Runoff is made-up of all sub-basins with observed measurements of regulated flow into Mono Lake, which are outlined in **Figure 2-2**.

Figure 2-14

Percent of Mono Lake's water budget (average annual storage) that is driven by different major components throughout the Mono Basin. Figure is based on the historical average contribution from each component from the MLWB simulated with several downscaled global climate models (later discussed). Assumes 16,000 ac-ft for exports and a 6,385 ft water level for the surface area calculation of precipitation (P), evaporation (PET), and ungauged runoff. The average annual acre-feet of each component is displayed in the figure as well.

Exports from Mono Lake
-16,000 ac-ft

Sierra Nevada Runoff
141,239 ac-ft

4.0%

35.2%

45.4%

Evaporation from Mono Lake
-180,553 ac-ft

8.6%

6.7%

Ungauged Runoff
34,419 ac-ft

Precipitation on Mono Lake
26,680 ac-ft
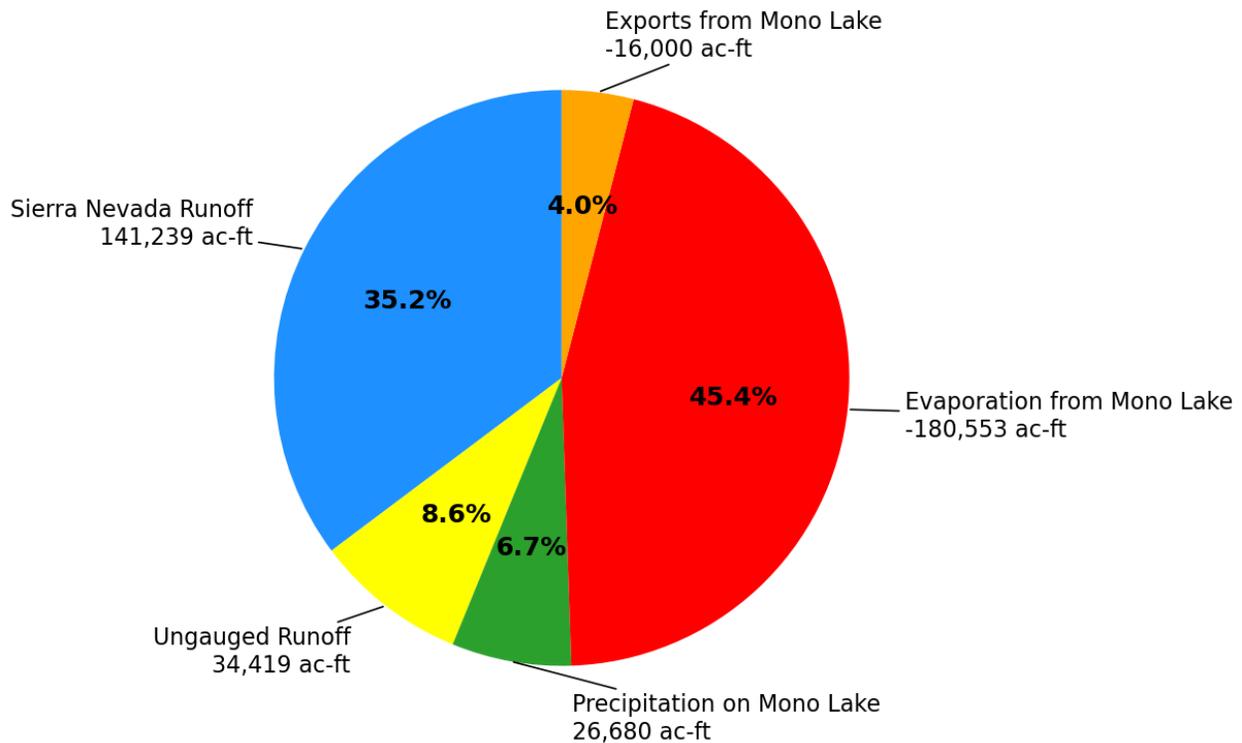
In the development of the MLWB, any required decisions or assumptions were informed via quantitative comparisons to observed data and the ability to represent Mono Lake's observed water level. While a reliable MLWB set-up was developed, slightly different choices could have been made. **Appendix A.4** (**Table A-4**, **Figure A-18**) provides a sensitivity analysis of the MLWB to alternative configurations. These tests show that changes to the MLWB setup produce relatively small differences in performance, confirming the robustness of the chosen configuration. Furthermore, **Figure A-19** demonstrates minimal variation in the probability of Mono Lake reaching different lake levels across alternative assumptions, reinforcing the MLWB stability under different configurations. For example, the similarity in the likelihood of being at or above critical water levels, demonstrates that the results provided throughout the report are relatively insensitive to alternative assumptions that could have been made in the set-up of the MLWB.

As discussed in the following section (**Section 3**), the workflow used to project Mono Lake water level under climate change relies on a similar modeling framework to that of ERA5-WRF.

Therefore, demonstrating ERA5-WRF's ability to accurately represent observed Mono Lake water level provides confidence in using a similar model set-up for climate projections. With strong alignment with past conditions (e.g. **Figure 2-13**) and the trends that drive the MLWB (e.g. **Figure 2-4b**), the UCLA-MLM provides a robust foundation for integrating climate change simulations, making it a valuable tool for future water resource planning and management in the Mono Basin.

Section 3 introduces the GCM-based hydroclimate forcing data used to assess Mono Lake's response to climate change and **Section 4** evaluates Mono Lake's projected water level under a range of export criteria using the climate projection framework.

3   21ST CENTURY HYDROCLIMATE SIMULATIONS

A central function of the UCLA-MLM is to evaluate whether climate change has influenced and is likely to continue to influence Mono Lake conditions. As a part of this evaluation, GCMs are used to assess climate change impacts over the historic period as well as project future climate change impacts. GCM simulations are particularly well suited for this because they characterize climate conditions over long periods of time. This is critical in the interpretation of climate change influences, because it allows scientists to identify long-term climate-trends and distinguish them from short-term variations in weather, or internal variability. Internal variability—such as fluctuations in sea surface temperatures in the Pacific known as the Pacific Decadal Oscillation and the El Niño Southern Oscillation—can drive changes over years to a decade (e.g. Bass et al. 2022; Lehner et al. 2018). However, climate trends refer to persistent, longer-term shifts in average conditions over multiple decades or more.

Using multiple GCMs, referred to as an ensemble, is also essential for a robust climate change analysis, as this helps account for complexities and uncertainties in the climate system. To assess climate change impacts in the historical period, an ensemble of GCMs representing historical conditions is compared with modeled observations. Consistency between trends from GCMs in the historical period and observed data increases confidence that climate change has played a role in observed conditions. Similarly, for trends or changes in the future, consistency across GCMs suggests higher confidence that a given change will occur.

This section describes the GCMs selected for this evaluation and their integration into UCLA-MLM. As in the previous section, the organization of this section is guided by a process-oriented flowchart (Figure 3-1) that outlines the key technical steps used to apply climate change scenarios as input to the MLWB. Each subsection that follows corresponds to a stage of this workflow. Section 3.1 through Section 3.3 rely on data that were developed as a part of the CA5. As such, these sections focus on general information associated with the climate datasets and provide readers with fundamental climate change concepts, while technical details can be obtained from CA5 Data Summaries (California Energy Commission, 2025). To develop climate simulations for CA5, GCMs and emission scenarios were selected (Section 3.1). These represent the climate at a coarse resolution (roughly 100 x 100 km resolution). Then, the GCMs atmospheric data were downscaled to a 3 x 3 km resolution (Section 3.2) and a hydrology model was forced using the downscaled GCM atmospheric data (Section 3.3). Together, these steps support UCLA-MLM's ability to simulate lake level responses to climate change under historic and future conditions. Lastly, the MLWB was run using the downscaled GCM atmospheric and hydrology data as the forcing data and an initial analysis of climate change impacts is performed (Sections 3.4-3.6). Section 3.4 provides a brief explanation of the metrics used in climate change assessment. Sections 3.5 and 3.6 present historical and projected trends in key components of the MLWB (e.g., precipitation, evaporation, runoff) and their combined impact on Mono Lake storage.

Figure 3-1

*Schematic demonstrating how climate simulations are applied to the MLWB. Note that the overall workflow for applying the simulated observed data (ERA5-WRF) from **Figure 2-1** is very similar, with the main difference being the usage of GCMs rather than ERA5-WRF as input to the MLWB*
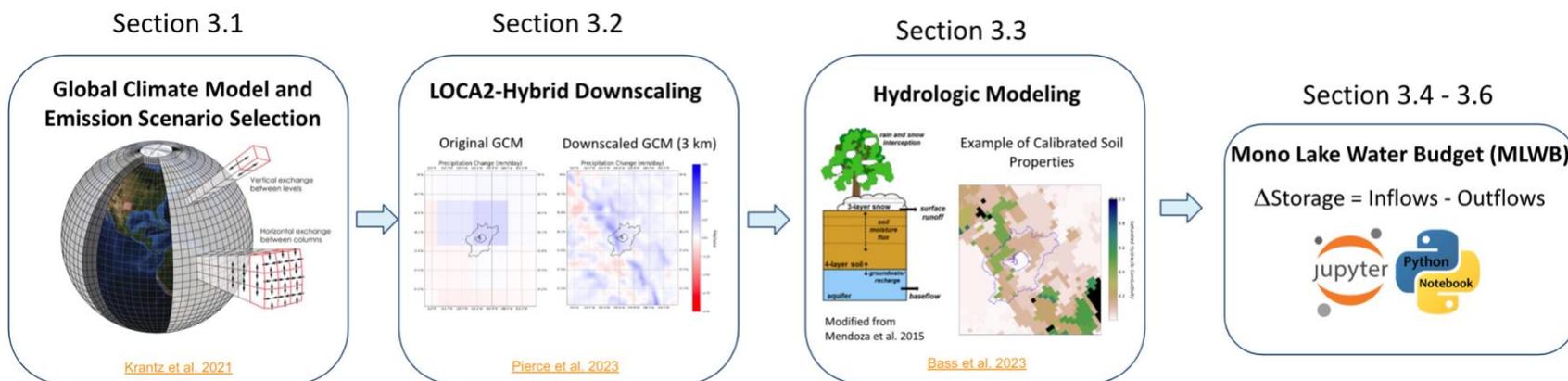
3.1 Global Climate Model & Emission Scenario Selection

3.1.1 Global Climate Models

Global Climate Models (GCMs) are powerful tools used to understand and predict changes in the Earth's climate over time. GCMs simulate the Earth's climate system, including the atmosphere, oceans, land surface, and ice, allowing for analysis of how various factors influence global temperatures, precipitation patterns, and other climate variables. GCMs rely on mathematical equations to simulate the physical processes that drive the Earth's climate. For example, GCMs model how solar radiation warms the Earth, heat exchanges between the surface and atmosphere, and represent cloud formation and dynamics. By simulating these processes, GCMs can evaluate how different greenhouse gas emission scenarios may alter future climate conditions.

Many different GCMs are created and run by research centers around the world. Each of these GCMs take a slightly different approach to modeling the climate system, varying in how they mathematically represent different complex processes. The Coupled Model Intercomparison Project Phase 6 (CMIP6) is the latest international effort to coordinate between different modeling groups and collaboratively advance climate modeling capabilities (Eyring et al. 2016). CMIP is updated in phases approximately every 5 to 8 years, with the most recent CMIP6 released in 2019. CMIP6 establishes a consistent framework for modeling past, present, and future climate conditions, which allows for the integration of outputs from different GCMs. These coordinated simulations provide the scientific basis for climate assessments, including those by the Intergovernmental Panel on Climate Change (IPCC).

Each GCM's distinct characteristics influence its suitability for regional applications, including spatial resolution, representation of physical processes, and the capacity to calibrate parameters to reflect historical conditions. As part of CA5, the GCMs most suitable to represent climate in California were identified based on their ability to simulate weather processes key to the region. This evaluation led to the selection of GCMs that better represent large-scale processes affecting California weather while also having lower biases in simulating regional temperature, precipitation, and other climate variables (Krantz et al. 2021). This GCM evaluation resulted in the selection of 11 GCMs listed in **Table 3-1** that include both atmospheric and hydrologic output across the three emission scenarios considered in CA5 (discussed in next section). In **Table 3-1** the names of the GCMs reflect the diverse international climate modeling centers responsible for their development, and the variant represents a unique initial condition associated with the specific GCM that was downscaled.

Table 3-1.

The 11 Global Climate Models (GCMs) used in this report.

GCM Name	Variant	Center	Native Resolution
ACCESS-CM2	r1i1p1f1	Commonwealth Scientific and Industrial Research Organization	1.25 deg × 1.25 deg
CNRM-ESM2-1	r1i1p1f2	Centre Européen de Recherche et de Formation Avancée en Calcul Scientifique	1.4 deg × 1.4 deg
EC-Earth3-Veg	r1i1p1f1	EC-Earth Consortium	0.7 deg × 0.7 deg
FGOALS-g3	r1i1p1f1	Chinese Academy of Sciences	2 deg × 2 deg
MIROC6	r1i1p1f1	Japan Agency for Marine-Earth Science and Technology	1.4 deg × 1.4 deg
MPI-ESM1-2-HR	r1i1p1f1	Max Planck Institute	0.94 deg × 0.94 deg
KACE-1-0-G	r1i1p1f1	National Institute of Meteorological Sciences	1.25 deg × 1.25 deg
MRI-ESM2-0	r1i1p1f1	Meteorological Research Institute	1.125 deg × 1.125 deg
GFDL-ESM4	r1i1p1f1	Geophysical Fluid Dynamics Laboratory	1 deg × 1 deg
IPSL-CM6A-LR	r1i1p1f1	Institut Pierre-Simon Laplace	1.25 deg × 1.25 deg
INM-CM5-0	r1i1p1f1	Institute of Numerical Mathematics	1.5 deg × 1.5 deg

Using multiple GCMs is essential for robust climate change analysis, in order to represent the range of possible future climate outcomes that can result due to differences in GCM model structures, parameterizations, and initial conditions (Knutti, 2010). Despite advancements in climate modeling, there are inevitable uncertainties in GCM simulations due to factors such as limitations in modeling complex processes and the climate system's inherent chaotic nature. Using an ensemble of high performing GCMs, rather than attempting to identify and use only the single best performing GCM, enhances the capacity to capture the range of uncertainty in predicting climate responses to these uncertainties. The resulting ensemble of GCMs used in the UCLA-MLM provides a range of plausible future outcomes, supporting more informed decision-making by accounting for uncertainty in long-term climate projections.

3.1.2 Shared Socioeconomic Pathways (SSPs)

CMIP6 simulates GCMs under historical emissions and different greenhouse gas emission trajectories, known as Shared Socioeconomic Pathways (SSPs). Different SSPs exist to allow for assessments of how varying levels of emissions related to different societal choices may influence future climate change. Different SSPs are used since it is unknown what emissions may actually be realized. On the other hand, historical emissions are known, and they are commonly used to assess climate change in the historical period.

The 11 GCMs simulate the historical period from 1955 to 2014 using observed emissions, meaning there is no divergence among the three SSPs prior to 2015. The portion of a GCM simulation covering this period is typically referred to as the *historical simulation*. In contrast, simulations from 2015 onward are based on projected emission scenarios and are referred to as scenarios or projections.

The UCLA-MLM focuses on the three SSPs available from CA5: SSP2-4.5, SSP3-7.0, and SSP5-8.5. These scenarios were selected because they span a range of plausible future emissions scenarios, from moderate (SSP2-4.5) to very high (SSP5-8.5), relative to historical levels (Fifth National Climate Assessment, 2023). The GCMs from CA5 simulate climate change impacts during the historical period using observed emissions from 1955 to 2014, and project future climate change from 2015 to 2100 based on different SSPs. Below, a description of each SSP is provided:

SSP2-4.5 includes moderate efforts to mitigate climate change and reflects a world with gradual progress toward sustainability. In SSP2-4.5, greenhouse gas emissions initially increase until 2050, and then emissions decrease by roughly half of present-day values by 2100. Under SSP2-4.5, by 2100, the radiative forcing is expected to be 4.5 W/m^2, leading to a global temperature increase of around 2.5°C above pre-industrial levels.

SSP3-7.0 is often considered an intermediate-high or "business as usual" scenario, where global efforts to reduce greenhouse gas emissions are limited. There is a continued reliance on fossil fuels, leading to high emissions and a radiative forcing of 7.0 W/m^2 by 2100. Under SSP3-7.0, the global temperature increase is projected to be around 3.2°C to 4.0°C above pre-industrial levels. One important caveat for this scenario is that it assumes leniency in future air quality policies and therefore has distinctively high aerosol emissions compared to the other SSPs. As a result, aerosol effects on precipitation may obscure the relationship between greenhouse gas emissions and precipitation changes (Shiogama, 2023).

SSP5-8.5 is often referred to as the "worst-case scenario" and assumes rapid economic growth fueled by intensive fossil fuel use. The radiative forcing reaches 8.5 W/m^2 by 2100, leading to a global temperature rise that could exceed 4°C. This scenario is used to explore the potential consequences of very high emissions and limited mitigation in emissions, making it a critical case for understanding the upper bounds of climate risks.

Respectively, SSP2-4.5, SSP3-7.0, and SSP5-8.5 represent an intermediate (emission) scenario, an intermediate-high scenario, and a very high scenario (Fifth National Climate Assessment, 2023). There is substantial uncertainty associated with which emission scenario will be realized; however, SSP2-4.5 and SSP3-7.0 are generally considered more likely than SSP5-8.5 (Huard, 2022).

3.2   Downscaling for Regional Resolution Using LOCA2-Hybrid

For the historical simulations and each of the three SSPs, the 11 GCMs were downscaled over California to better analyze regional climate changes. GCMs operate at coarse spatial resolution, often roughly equal to or exceeding 100 x 100 km grid cell resolution, which limits their ability to capture regional and local-scale climate variations. For example, a single GCM grid cell can cover the entirety of the Mono Basin. To address this, GCM outputs must be downscaled to generate climate simulations with finer spatial detail suitable for regional analyses, particularly in topographically complex areas like the Mono Basin.

CA5 employed the Hybrid Localized Constructed Analogs version 2 (LOCA2-Hybrid) method to downscale selected CMIP6 GCMs to a spatial resolution of 3 km (Pierce et al., 2023b). This approach enhances the representation of regional climate conditions by incorporating elements of two downscaling methods, statistical and dynamical. Dynamical downscaling is a method used to produce high-resolution climate information by running a regional climate model (RCM) that is physically based and driven by larger-scale climate data from a global climate model (GCM) or atmospheric reanalysis. While statistical downscaling provides a computationally efficient method to produce high-resolution climate information based on statistical relationships between large-scale climate variables and local climate conditions. The hybrid method used here combines the computational efficiency of statistical downscaling with the ability of dynamical downscaling to physically represent atmospheric conditions. Specifically, LOCA2-Hybrid builds on traditional statistical downscaling, which uses a pattern library containing only historic observations, by integrating atmospheric circulation patterns derived from dynamical downscaling projections across the 21st century. This integration improves performance in mountainous terrain where statistical methods alone can underperform and avoids an assumption of stationarity employed by previous versions of LOCA2.

As a part of the LOCA2-Hybrid downscaling workflow, the GCMs are bias corrected to ERA5-WRF reanalysis data using the Preservation Ratio (PresRat) technique, which maintains long-term trends (Pierce, 2015). Furthermore, the downscaled GCMs atmospheric (and hydrology) data was adjusted to reflect the Mono Basin specific adjustments that were applied to ERA5-WRF for this report (outlined in **Appendix A.2.1**). The LOCA2-Hybrid dataset used in CA5 represents the most recent and comprehensive CMIP6 downscaling effort available for California and supports a wide ensemble of GCM and emission scenario combinations due to its computational efficiency. Further details regarding the LOCA2-Hybrid method and the PresRat technique are beyond the scope of this report but can be found in Pierce et al. 2023b and Peirce 2015, respectively.

3.3 Hydrology Simulations

As outlined in **Section 3.2**, high-resolution atmospheric data were generated by downscaling 11 GCMs for each of the three SSPs using LOCA2-Hybrid. These climate simulations provided inputs, such as precipitation and temperature, for a calibrated hydrology model, Noah-MP, to simulate key hydrologic conditions across California as a part of CA5 (Bass et al. 2023). This is the same hydrology model described in **Section 2.1.2** that was also used to simulate observed hydrologic conditions with ERA5-WRF data. The only difference here is that, instead of ERA5-WRF atmospheric inputs, the hydrology model was driven by downscaled atmospheric data from GCM simulations. By applying future climate scenarios, the hydrology model produces spatially distributed estimates of surface runoff or natural flow across California.

The UCLA-MLM hydroclimate modeling framework uses an ensemble of 33 projections (11 GCMs x 3 SSPs) providing high-resolution (3 km x 3 km) simulations of atmospheric and hydrologic conditions across California. From this ensemble, atmospheric and hydrologic data relevant to MLWB were extracted. To improve consistency with observed conditions, the same mean-state adjustments made to the ERA5-WRF data (outlined in **Appendix A.2.1**) were applied to the climate projections. Aside from details provided in **Appendix A.3**, the MLWB remains largely unchanged from its usage with ERA5-WRF, and its set-up described in **Section 2.2**.

Importantly, the instream flow requirements (IFRs), which dictate the volume of water that must flow throughout the runoff year in the Mono Basin's major creeks (described in **Appendix A.3.2**), were updated for each GCM simulation. Every 5-years, the MLWB calculates IFRs based on the preceding 50-years of simulated four-creek natural flow. This dynamic update process follows guidance from LADWP's Mono Basin Operations Plan (MBOP) (Los Angeles Department of Water and Power, 2022) and reflects variability in runoff year types.

3.4 Metrics Used to Assess Climate Change

The UCLA-MLM was developed to simulate Mono Lake level dynamics under both historical and projected climate conditions, focusing on how key components of the MLWB—including precipitation, evaporation, Sierra Nevada runoff, and ungauged runoff—respond to climate change. These hydrologic variables exhibit both temporal and spatial variability across the Mono Basin, particularly in relation to precipitation patterns. To evaluate potential future impacts on Mono Lake's water level, UCLA CCS conducted a comprehensive analysis of how key MLWB components may evolve under different climate scenarios. This section outlines the statistical methods used to assess climate-driven change used throughout this report.

As described in **Section 3.1.1**, using an ensemble of General Circulation Models, also referred to as Global Climate Models (GCMs)—rather than relying on a single best-performing GCM—enhances the ability to account for uncertainty in climate modeling. Typically, statistics are derived from an ensemble of GCMs to evaluate potential future changes. **The primary metrics used in this report include:**

i) The **ensemble mean**, representing the most likely outcome from an ensemble of GCM climate simulations;

ii) The **standard deviation**, indicating variability across GCMs. One standard deviation is commonly used in climate change assessments (IPCC, 2023);

iii) The **agreement on direction of change** (e.g., drying or wetting), expressed as the percentage of GCMs that concur. A wetting or drying condition is considered likely when 2/3rds (66.7%) of GCMs agree on the direction of change (Mastrandrea, 2011). For this report, if 8 out of 11 GCMs (72.7%) project an increase or decrease in a variable during a specific period, the direction of change is considered "likely," even if the exact amount of change varies across GCMs; and

iv) The **likelihood** or **probability** of a condition occurring is assessed by the percentage of GCMs that agree on a specific change. This metric is commonly used to evaluate the likelihood of being at or above a particular water level (see **Section 4**), but it is also used in assessing changes in storage (e.g. **Section 3.6**). Descriptions of likelihoods presented throughout the report are based on numeric ranges used by the IPCC and the National Climate Assessment (**Table 3-2**).

Table 3-2.

The likelihood scale from Mastrandrea et al. (2011) used by the IPCC and incorporated in this report to associate ranges of likelihoods with descriptive terms.

Term	Likelihood (probability, %)
Virtually certain	99 – 100%
Very likely	90 – 100%
Likely	66 – 100%
About as likely as not	33 – 66%
Unlikely	0 – 33%
Very unlikely	0 – 10%
Exceptionally unlikely	0 – 1%

The use of statistical measures to summarize projections from an ensemble of GCMs is standard practice in climate change research (IPCC, 2023). Additionally, because internal variability causes each GCM to simulate unique sequences of annual conditions, such statistics are typically evaluated over time periods greater than a single year. For example, in assessing climatological shifts, 30 years is commonly used (IPCC, 2023). This 30-year

averaging approach is a standard practice in climate science, as it effectively captures climatological conditions for the historical time-period and future time-periods of interest, while minimizing the influence of short-term variability (IPCC, 2023). Using this averaging approach reduces the year-to-year noise, while highlighting trends if they exist. While climatological averaging is essential for capturing climate change conditions for many variables, others—such as storage and Mono Lake water level—are influenced by cumulative changes. This dampens interannual variability, as their state in any given year reflects the accumulation of conditions from preceding years. However, large variations in water level for individual dry or wet years due to internal variability associated with individual GCMs can still influence the ensemble mean water level. As such, climate change evaluations of water level, provided later in **Section 4**, extract statistics based on 5-year averages of water level.

The historical conditions compared against include the mean and standard deviation statistics from the first 30-years available from the GCMs, which include 1955–1985. The projected conditions for each MLWB component are obtained for every 30-year period from 1955 to 2100 and compared against this historical time-period to assess how conditions have already changed and may continue to change throughout the 21st century. For example, to assess projected evaporation in 2070, the GCM ensemble mean for 2039–2069 is compared against the GCM ensemble mean for 1955–1985. This comparison is repeated annually through 2100, creating a continuous series of 30-year averages that reflect expected climate-driven changes over time. The 30-year rolling average better reflects the climatological trend rather than inter-annual variations that can be influenced by internal variability. A projected average falling below the historical average suggests a modeled decrease due to climate change while an average above indicates a projected increase. This methodology is applied consistently across all MLWB components. There is greater confidence that a change is likely when GCMs demonstrate agreement on the direction of change, and greater agreement on the magnitude of change when the standard deviation is narrower.

This same method is used to assess if climate change has influenced present-day conditions. When an observed trend, here, represented by ERA5-WRF (described in **Section 2**), is also reflected in the ensemble mean of GCMs—and when there is strong agreement among the GCMs on the direction of change—it increases confidence that the observed trend is attributable to climate change. In contrast, a divergence between the ERA5-WRF trend and ensemble GCM trend indicates little or no detectable climate signal in the observed data. For example, to assess evaporation in 2024, the GCM ensemble mean for 1994–2024 can be compared against the GCM ensemble mean for 1955–1985. If the GCMs concur that a positive or negative change has occurred for a given variable like evaporation from the 1985 to 2024, then there is greater confidence that climate change has likely led to a change in that variable.

3.5   Climate-Driven Changes Across the Mono Basin

This section presents historical and projected atmospheric and hydrologic (hydroclimate) changes for key MLWB variables. It describes how climate change may alter conditions in the Mono Basin and, in turn, affect Mono Lake's water level. Climate impacts for the Mono Basin are discussed first, followed by Mono Lake water level projections in **Section 4**. This

sequencing helps clarify how climate-driven changes—and their associated uncertainties—inform water level outcomes.

3.5.1 Changes in MLWB Components

In **Figure 3-2** historic and projected changes in the major components of the MLWB are summarized, including: precipitation over Mono Lake, evaporation from Mono lake, Sierra Nevada runoff (which includes gauged basins from **Figure 2-2**), and ungauged runoff. For conciseness, projected changes are shown under SSP3-7.0; however, projections for SSP2-4.5 and SSP5-8.5 are available in **Appendix Figure B-1**. In general, relative to SSP3-7.0, SSP2-4.5 shows similar patterns of GCM agreement but with slightly smaller projected changes, whereas SSP5-8.5 exhibits both greater agreement among GCMs and more pronounced changes. **Figure 3-2** also includes the modeled observations. The historical simulations from the GCMs represent an ensemble of possible trends arising from internal climate variability and differences in how each GCM simulates that variability. In contrast, the modeled observations reflect the specific sequence of internal variability that occurred, including an anomalously wet period prior to 2000 followed by a prolonged dry period after 2000. As a result, the trend in the modeled observations reflects the realized internal variability, whereas the GCM ensemble represents the range of variability that could occur but does not reproduce the exact observed sequence. The results are presented as 30-year rolling averages to reduce interannual variability. Below, climate-driven changes for key MLWB variables are described:

Evaporation. All GCMs indicate that lake evaporation has already increased due to climate change (post-2000) and will continue to rise throughout the century (**Figure 3-2b**).

Precipitation. Prior to 2040, GCMs do not agree on a particular change in precipitation, and the ensemble mean change is nearly neutral. However, by 2050 onward, most GCMs project an increase in lake precipitation (**Figure 3-2a**), though the signal is less uniform than for evaporation.

Runoff. Sierra Nevada runoff shows some agreement in a decrease (**Figure 3-2c**), while ungauged runoff shows some agreement in an increase (**Figure 3-2d**). As a result, total runoff is not projected to increase or decrease with high confidence (**Figure 3-2f**).

Water Budget Implications. The increase in evaporation already has and is projected to continue to outpace future increases in precipitation (**Figure 3-2e**), potentially worsening lake level declines unless offset by changes in inflows or management.

Figure 3-2

*Changes in components of Mono Lake's water budget for SSP3-7.0 (**Appendix Figure B-1** includes results for SSP2-4.5 and SSP5-8.5). Different colored lines represent each of the 11 GCMs. Black line represents the GCM ensemble mean with a solid line indicating 2/3rds GCM agreement on the direction of change (positive or negative) for a given time in the future compared to historical conditions (average from 1955 to 1990 for this plot). Grey shading represents 1 standard deviation. Red line represents modeled observations (ERA5-WRF).*
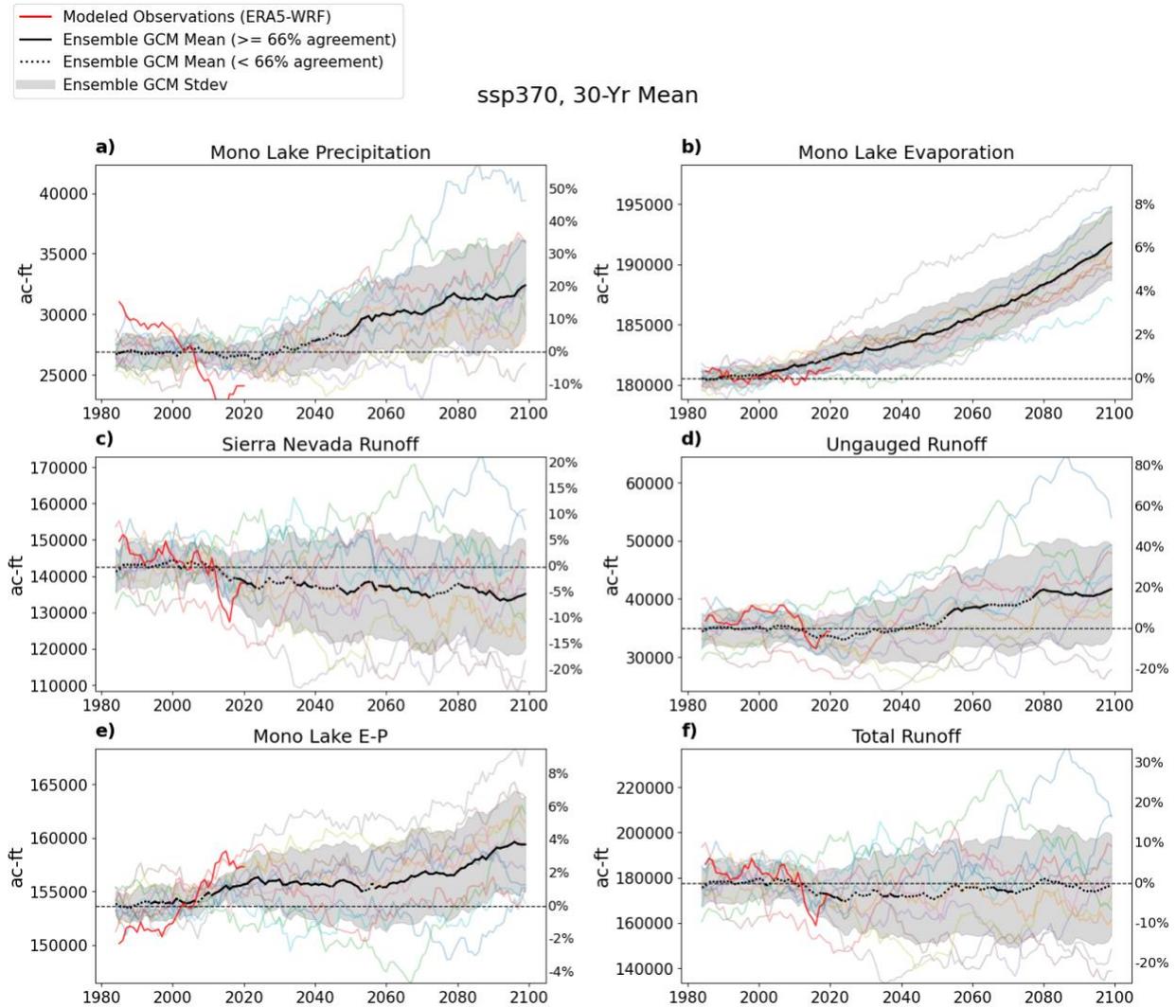
3.5.2 Attribution of Observed Changes

Comparison of the climate simulations to modeled observations (ERA5-WRF) offers insight into the extent to which recently observed changes may already reflect climate impacts. Since the GCMs and modeled observations demonstrate an increasing trend in evaporation, the observed increases in evaporation represented by modeled observations are likely associated with climate change (**Figure 3-2b**). Conversely, for precipitation, the ensemble mean GCM trend does not align with ERA5-WRF (**Figure 3-2a**). While modeled observations show a general decline in precipitation, this pattern is not replicated in climate-driven model simulations, implying the decline in precipitation is likely due to long-term weather variability rather than climate change. These findings generally agree with other studies evaluating the anomalously dry conditions from 2000 to 2022 (Williams, 2022) which is partially tied to a cool Pacific Decadal Oscillation phase (Bass et al. 2022). Finally, although the GCM ensemble mean indicates a decreasing trend in total runoff, fewer than two-thirds of the GCMs agree that climate change has contributed to this decline during the historical period (**Figure 3-2f**). Therefore, the downward trend in total runoff observed in modeled observations is not likely due to climate change.

3.6 Climate-Driven Changes in Mono Lake Storage

The trends for key water budget components were combined to assess Mono Lake storage under historical emissions and each emissions scenario (SSP). This analysis uses the MLWB equation (**Section 2**) to determine storage, with surface LADWP exports set to zero to isolate the effects of climate change. Annual changes in storage were assessed, rather than the cumulative changes, to further understanding of the expected changes in Mono Lake storage for a given time-period.

The annual changes are shown in **Appendix Figure B-2**, but here a key question relative to existing export criteria is explored: Can changes in Mono Lake storage support the level of LADWP exports currently allowed under the existing Amended Licenses (~16,000 ac-ft/yr)?

For each year (e.g., 2070), the percentage of GCMs projecting an annual storage change above 16,000 ac-ft/yr was calculated (**Figure 3-3**). If this percentage reaches the threshold of 72.7% (8 of 11 GCMs), the annual increases in Mono Lake storage are considered likely to offset typical LADWP exports. In the historical period, or up to roughly 2014, the majority of GCMs indicate 16,000 ac-ft/yr exports can be maintained without reducing Mono Lake storage. However, results from 2024 onward indicate that 2/3[rds] GCM agreement, the threshold for a likely outcome used in climate change analysis (IPCC, 2023), is rarely met. For SSP2-4.5, only a few future years exceed the 2/3rd GCM threshold, and this threshold is never met for SSP3-7.0 and SSP5-8.5, with SSP5-8.5 consistently showing the lowest projected storage gains. This aligns with SSP5-8.5 producing the greatest evaporation increases and the least precipitation-driven offset of the emission scenarios considered (**Figure B-1**).

Figure 3-3

Percent of GCMs with a net change in storage greater than 16,000 ac-ft, using all components that make up the MLWB but no exports. In this assessment, the MLWB was simulated with the climate projections using an initial water level of 6383.7 ft (April 1st, 2024 water level) and no exports were allowed.
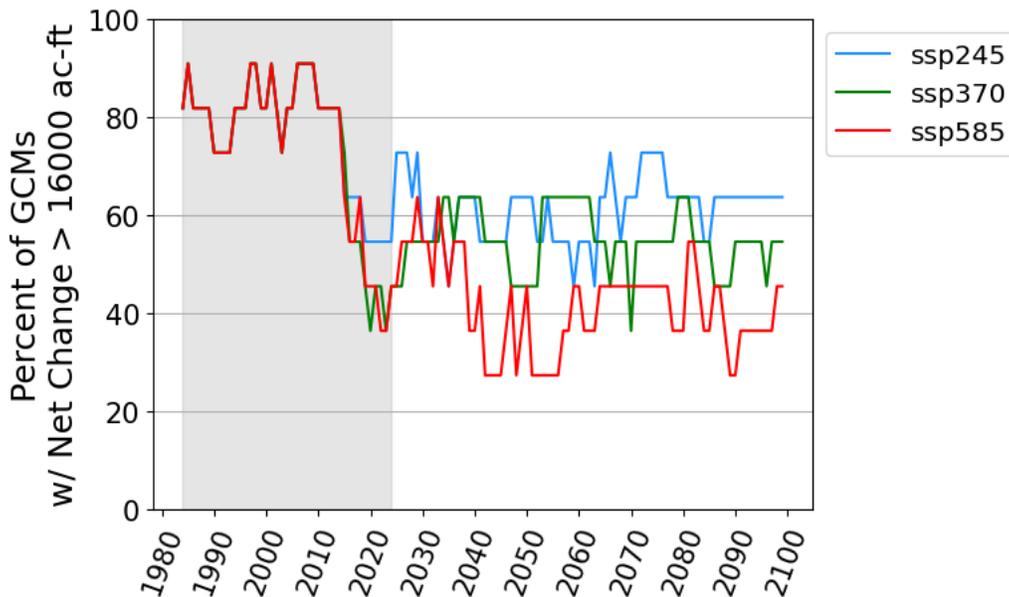
The percent of GCMs showing positive changes in storage is also included in the Appendix (**Figure B-3**). Notably, every GCM shows positive changes in storage during historical emissions (up to 2014); however, by 2024 onward, the percent of GCMs experiencing positive changes in storage begins to decline.

3.6.1 Projected Temperature Change

An ancillary analysis was conducted to demonstrate spatial changes in temperature and precipitation across the Mono Basin. Generally, increases in temperature can drive increases in Mono Lake evaporation, and in the absence of precipitation gains, reduce runoff due to its impact on snowpack and evaporation. Changes in precipitation are more variable, but have a direct influence on Mono Lake precipitation, and influence runoff.

Changes in temperature and precipitation were assessed using 30-year climatological averages, comparing end-of-century projections (2070-2099) to the historical baseline (1955-1985) simulated by the GCMs. This baseline period was selected to minimize the influence of recent climate change, unlike more recent periods such as 1985-2015.

Figure 3-4 shows the spatial distribution of projected temperature change under SSP3-7.0, based on the mean change in 30-year average temperature (2070-2099 minus 1955-1985) calculated at each grid cell from the 11 GCMs. Results show a consistent warming of approximately 4 degrees Celsius across the Mono Basin and surrounding areas. All GCMs agree on a warming trend, highlighting high confidence in projected temperature increases.

Figure 3-4

Change in temperature for SSP3-7.0 across the Mono Basin based on the ensemble GCM average from 2070 to 2099 minus the historical average from 1955 to 1985. All GCMs agree that temperature will increase across the Mono Basin.
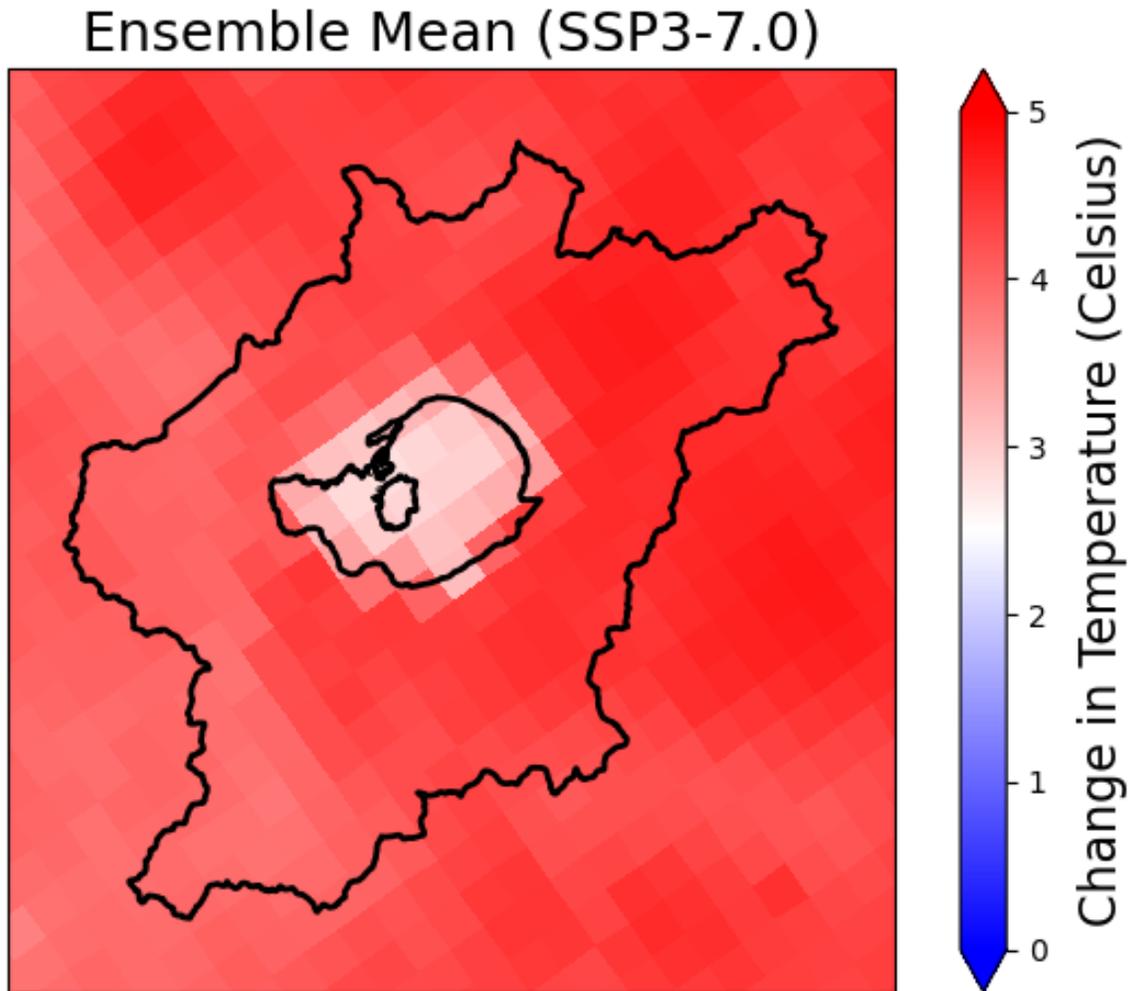
3.6.2 Projected Precipitation Change

Projected precipitation changes show greater variability both spatially and across GCMs. **Figure 3-5** shows the individual GCM projections, and the ensemble mean change in precipitation. For the ensemble mean (bottom right of **Figure 3-5**) the grey outline indicates areas where at least 2/3^{rds} (≥66.7%) of GCMs agree on the direction of precipitation change. While most GCMs predict an overall increase in precipitation across the basin, agreement is weaker in key headwater areas of the Sierra Nevada, or the western edge of the Mono Basin, that feed Mono Lake.

Figure 3-5

Change in precipitation for SSP3-7.0 across the Mono Basin for each individual GCM, and the ensemble mean shown in the bottom right. Change (in/yr) is based on the average from 2070 to 2099 minus the historical average from 1955 to 1985. Only the regions outlined in grey for the ensemble mean (bottom right) have greater than 2/3^{rds} agreement among the GCMs on whether precipitation will increase or decrease.
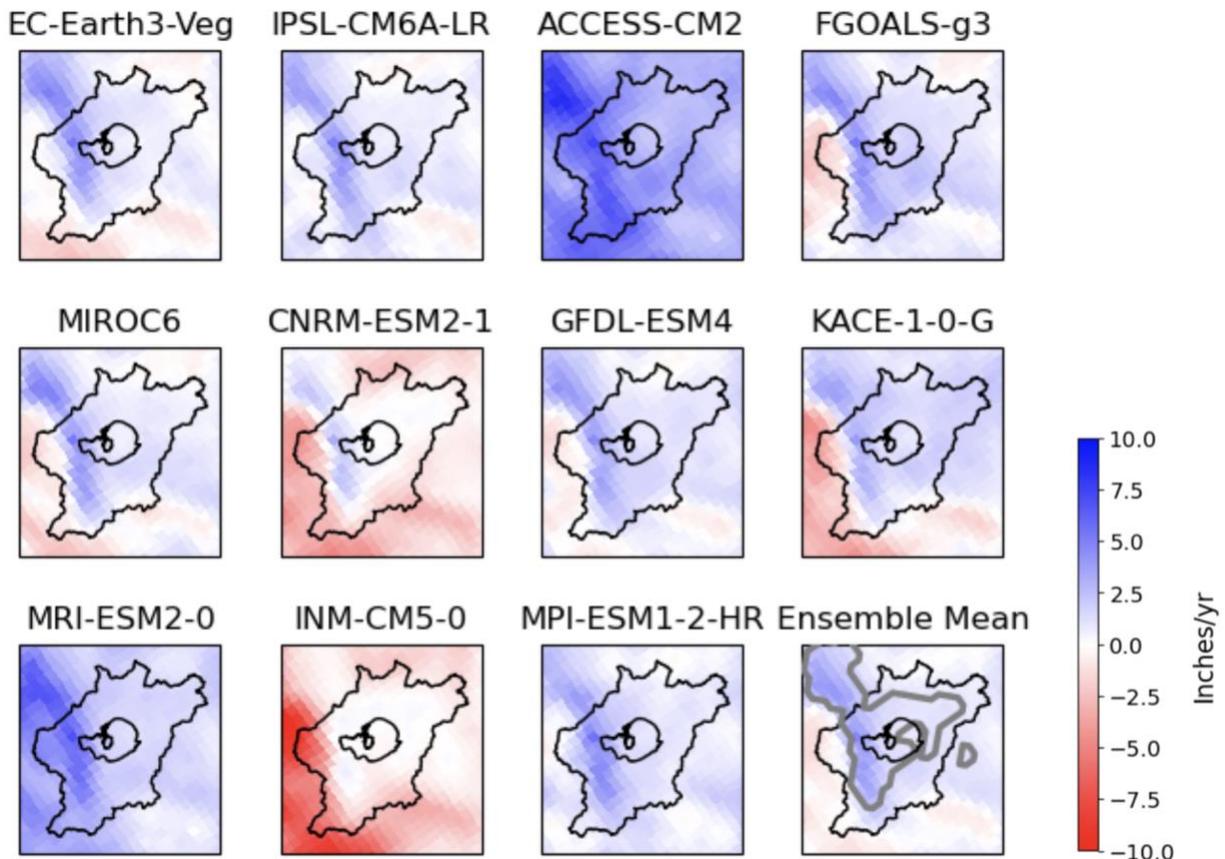
3.6.3 Summary of Key Findings

1. Evaporation from Mono Lake has already increased due to climate change and is projected to continue increasing across all SSPs.

2. Precipitation is projected to increase starting around 2050. Climate change does not appear to have significantly affected precipitation in recent decades.

3. There is some confidence that Sierra Nevada runoff is projected to decrease, while Ungauged Runoff is projected to increase. When considering total runoff from these two components, they offset one another and introduce a range of possible runoff outcomes. The range of runoff outcomes is driven by the range of precipitation projections.

4. The projected increases in evaporation outpace gains from precipitation, suggesting that, under most scenarios, increases in Mono Lake storage will not be sufficient to fully compensate for losses from typical LADWP exports of 16,000 ac-ft/yr.

4 MODELING MONO LAKE'S WATER LEVEL UNDER VARYING EXPORT CRITERIA AND CLIMATE CONDITIONS

In this section, water level estimates from the UCLA-MLM are presented. The primary objective in this section is to inform how Mono Lake's water level responds to different export criteria and climate assumptions. This includes evaluations of Mono Lake water level under recent climate conditions and existing export criteria, as well as projected water level estimates based on future climate conditions and alternative export criteria.

Below, the different parts of this section are outlined:

Section 4.1 presents an overview of Mono Lake's water level under a variety of assumptions. The purpose of this section is twofold: i) to demonstrate how existing exports impact Mono Lake's water level compared to no exports and ii) to demonstrate how climate change impacts Mono Lake's water level. Throughout **Section 4.1** analysis is limited to four possible export criteria that represent the lower (no exports) and upper (existing exports) bounds of exports that could occur in the transition and post-transition periods.

Section 4.2 outlines the performance of additional transition and post-transition export criteria combinations. This assessment is performed using climate projections, which provide a more realistic representation of plausible future conditions than assuming historical climate conditions will remain unchanged. **Sections 4.2.1** and **4.2.2** outline the rules associated with the alternative transition and post-transition export criteria developed by the MLTWG and UCLA CCS. **Section 4.2.3** and **4.2.4** outline the ability of the transition and post-transition export criteria to meet their respective objectives. And **Section 4.2.5** provides an evaluation of the transition and post-transition export criteria when combined, as they would be in practice based on D-1631.

General Information Critical to Section 4.

As a reminder, D-1631 describes two export criteria: i) a transition export criteria and ii) a post-transition export criteria. The transition criteria apply until the lake reaches 6,391 ft, at which point post-transition criteria take effect. Following D-1631 and MLTWG guidance, the alternatives in this report include a transition and post-transition period. D-1631 mandated that Mono Lake maintain an average water level of 6,392 ft once in the post-transition period to protect public trust resources (California State Water Resources Control Board, 1994).

The performance of the transition and post-transition export criteria are assessed based on their ability to meet their respective objectives of reaching 6,391 ft (**Section 4.2.3**) and maintaining a water level of 6,392 ft (**Section 4.2.3**). However, when the transition and post-transition criteria are combined, as they would be in practice based on D-1631, the main report focuses on the ability to maintain Mono Lake's water level above 6,391 ft given its relevance as the transition water level and its proximity to the post-transition target water level of 6,392 ft.

The ability to reach additional water levels is provided in **Appendix C** (reference for **Section 4.1**) and **Appendix D** (reference for **Section 4.2**).

Also, while several (84) alternatives are considered in this section, a UCLA-MLM User Interface (outlined in **Section 5**) is being developed where interested parties may be able to explore additional transition and post-transition strategies.

Finally, because this report was developed in 2024, MLWB simulations use the April 1, 2024 Mono Lake water level as an initial condition, unless otherwise specified. This starting point reflects both the timing of the analysis and the initial condition adopted by the MLTWG during the development of the UCLA-MLM. However, as noted earlier, a range of alternative initial water levels can be explored using the UCLA-MLM User Interface. For example, the water level has decreased slightly since April 1st, 2024: from 6383.7 ft on April 1st, 2024 to 6383.3 ft on April 1st, 2025.. While this initial water level difference is small and should not modify the general findings in this report, this highlights the benefit and importance of the UCLA-MLM User Interface for analysis based on evolving conditions.

4.1 Influence of Existing Exports and Climate Change on Mono Lake Water Level

Existing export criteria in D-1631 follows a tiered framework, allowing increased exports as Mono Lake reaches specific water levels (Table 4-1). This tiered framework applies for both transition and post-transition export criteria. Because the lake level has never reached 6,391 ft, the post-transition export criteria have not been activated. As a result, recent LADWP exports have varied between 4,500 and 16,000 ac-ft/yr since the existing export criteria was enacted in 1994.

Table 4-1

a) Transition Export Criteria and b) Post-Transition Export Criteria set by D-1631 in September 1994. This export criteria still applies at the time this report was written and has been adhered to since it was enacted. However, since a Mono Lake water level of 6,391 ft has not been reached, the post-transition criteria has not yet been used.

a) *Transition Export Criteria (effective until the lake reaches 6,391 ft)*

Lake Level	Diversion Volume
Below 6,377 ft	No Diversion Allowed
6,377 to 6,380 ft	4,500 ac-ft per year
6,380 to 6,391 ft	16,000 ac-ft per year

b) *Post-Transition Export Criteria (applies after lake reaches 6,391 ft and remains in place)*

Lake Level	Diversion Volume
Below 6,388 ft	No Diversion Allowed
6,388 to 6,391 ft	10,000 ac-ft per year
Above 6,391 ft	All allowable flows in excess of amounts needed for fishery protection flows

This section uses four export criteria (outlined in Table 4-2) to demonstrate how Mono Lake's water level is impacted by existing export criteria, no exports, and climate change. The export criteria considered represent the upper and lower export bounds that could occur in the transition and post-transition periods. *Existing Exports* represents the existing transition and post-transition export criteria as prescribed by D-1631. This represents the upper bound of exports considered. *No Exports* does not allow any exports at any water level and thus represents the lower bound. To evaluate the influence of the post-transition export criteria on Mono Lake's water level, two additional export criteria are considered. These include Existing

Exports (No Post-Transition) and No Exports (Yes-Post Transition). These two export criteria allow for exports that fall between the upper and lower export bounds that could occur and provide insight regarding the influence the post-transition export criteria can have on Mono Lake's water level.

Table 4-2

The four export criteria assessed in Section 4.1, which encompass the lower and upper bounds of exports that could occur in the transition and post-transition period.

Combination	Description
Existing Exports	This is the export criteria outlined in D-1631 for both and post-transition conditions **Table 4-1**.
Existing Exports (No Post-Transition)	This is the transition export criteria outlined by D-1631 (**Table 4-1a**) but does not trigger the post-transition export criteria. Rather, the transition export criteria continue to apply, with 16,000 ac-ft allowed above 6,391 ft.
No Exports (Yes Post-Transition)	This does not allow exports until 6,391 ft. After 6,391 ft is reached the post-transition export criteria outlined in **Table 4-1b** applies.
No Exports	This does not allow any exports at any water level.

Section 4.1.1 assesses if Mono Lake's water level would have reached the transition level of 6,391 ft if No Exports had been taken from 1994 to 2020 under weather conditions represented by modeled observations (ERA5-WRF). This simulation starts in 1994, when the existing transition exports were enacted, and was assessed by simulating the MLWB with Existing Exports and No Exports.

Section 4.1.2 assesses Mono Lake's water level with the four export criteria (Table 4-2) if observed weather conditions (from 1971 to 2020) were to repeat in the future. This evaluates Mono Lake's water level without climate change considerations.

Section 4.1.3 assesses the influence of climate change in the absence of exports.

Section 4.1.4 uses the four export criteria (Table 4-2) and climate change to assess Mono Lake's water level. This evaluates Mono Lake's water level using plausible future climate

conditions and the lower and upper bounds of exports that could occur in the transition and post-transition periods.

4.1.1 Impact of Existing Export Criteria on Historical Lake Level

Modeled observations (ERA5-WRF) were used to evaluate how exports have impacted Mono Lake's water level and how the lake level may have responded had LADWP elected to take no exports from 1994 to 2020 (since D-1631 to the last year available from ERA5-WRF). Since this assessment is driven by observed weather conditions, climate change considerations are not included.

Figure 4-1 shows the simulated water level from 1994 to 2021 using modeled observations (ERA5-WRF) with Existing Exports and No Exports. Unlike analyses in the remainder of **Section 4**, which focuses on Mono Lake's water level under future rather than past conditions, this assessment uses the observed water level on April 1, 1994 as an initial condition (6,375.1 ft). This comparison highlights the considerable impact of Existing Exports on the Mono Lake water level, which exhibits a 4 ft difference between Existing Exports and No Exports by 2021. However, even under No Exports, Mono Lake would not have reached the 6,391 ft transition water level over this 27-year time period. It is worth noting that No Exports assumes the Mono Craters Tunnel still would have intercepted and exported groundwater. The inability to reach 6,391 ft is thus likely due to a combination of factors, including a low initial water level condition in 1994, a negative trend in precipitation that was very likely driven by internal variability (reference **Figure 3-2**), and exports that took place. Relative to exports, which led to a 4 ft difference, climate change reduced Mono Lake water level by roughly 2.6 ft from 1994 to 2021. However, it is worth noting that in the estimate of climate change impacts on 2021 water level, roughly 2/3rds of the GCMs indicate reductions in Mono Lake's water level and there is a 6.0 ft spread in the standard deviation across the GCMs (**Appendix Figure C-24**).

Figure 4-1

Mono Lake water level from 1994 to 2021 for a simulation with Existing Exports (red line) and a simulation with No Exports (green line). This assessment was performed since D-1631 was enacted in 1994, with the initial water level based on observed conditions on April 1st, 1994 (6,375.1 ft). Post-transition export criteria were not used in this simulation since 6,391 ft was not reached.
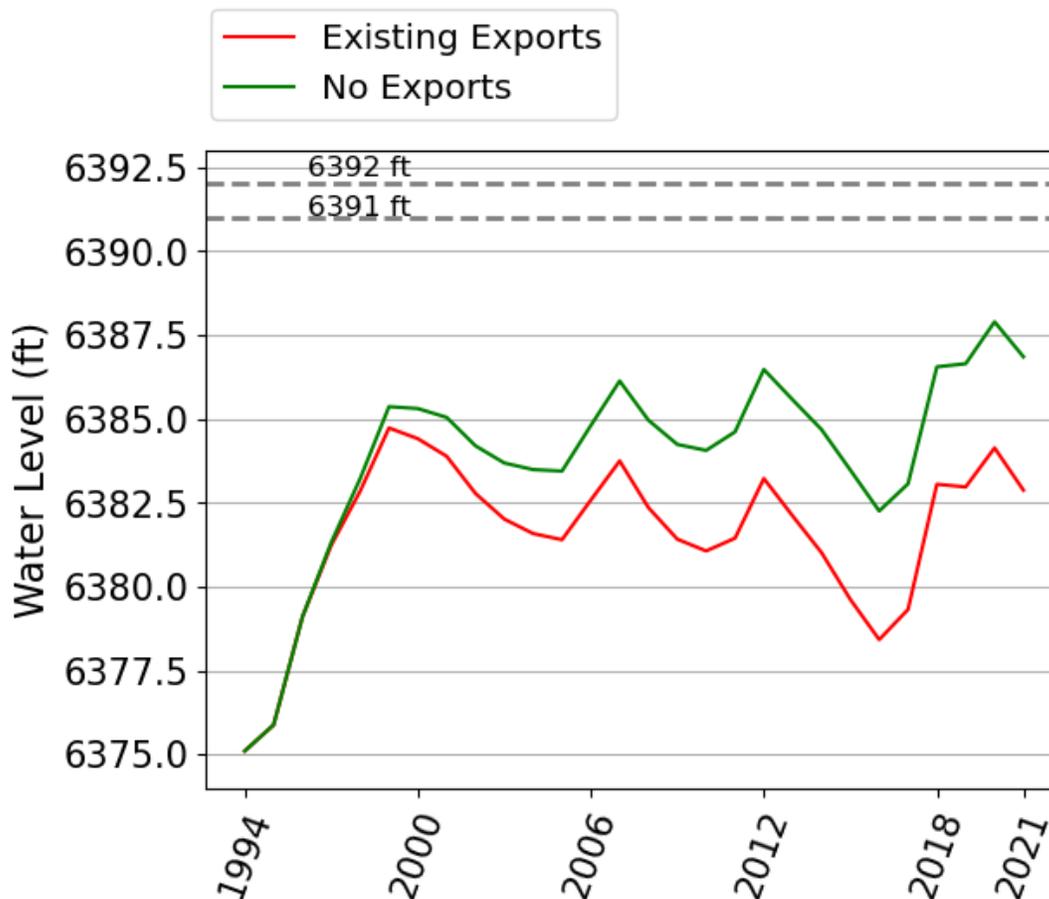
4.1.2 If Observed Weather Repeats Itself

Evaluating the impact of future exports in isolation, independent of future climate change, can be a helpful exercise to understand Mono Lake's water level in an optimistic scenario assuming climate change does not occur. The UCLA-MLM can use modeled observations (ERA5-WRF) to replicate historic atmospheric and hydrologic conditions that were experienced. For this assessment, the years 1971 to 2020 are considered since this 50-year period represents a recent climatological period which was also widely used by the MLTWG, including LADWP and MLC. This approach effectively projects into the future the same conditions observed in the past from 1971 to 2020, absent any influence from future climate change. **Figure 4-2** illustrates

lake levels over time under four export criteria representing the lower and upper bounds of exports that could occur in the transition and post-transition period (detailed in **Table 4-2**).

Figure 4-2

Simulated results with an initial water level of 6,383.7 ft which reflects conditions on April 1st, 2024. Simulation performed for each of the four export criteria outlined in **Table 4-2***. Note, this simply repeats the modeled observations from 1971 to 2020, as represented by ERA5-WRF, and does not consider future climate change.*
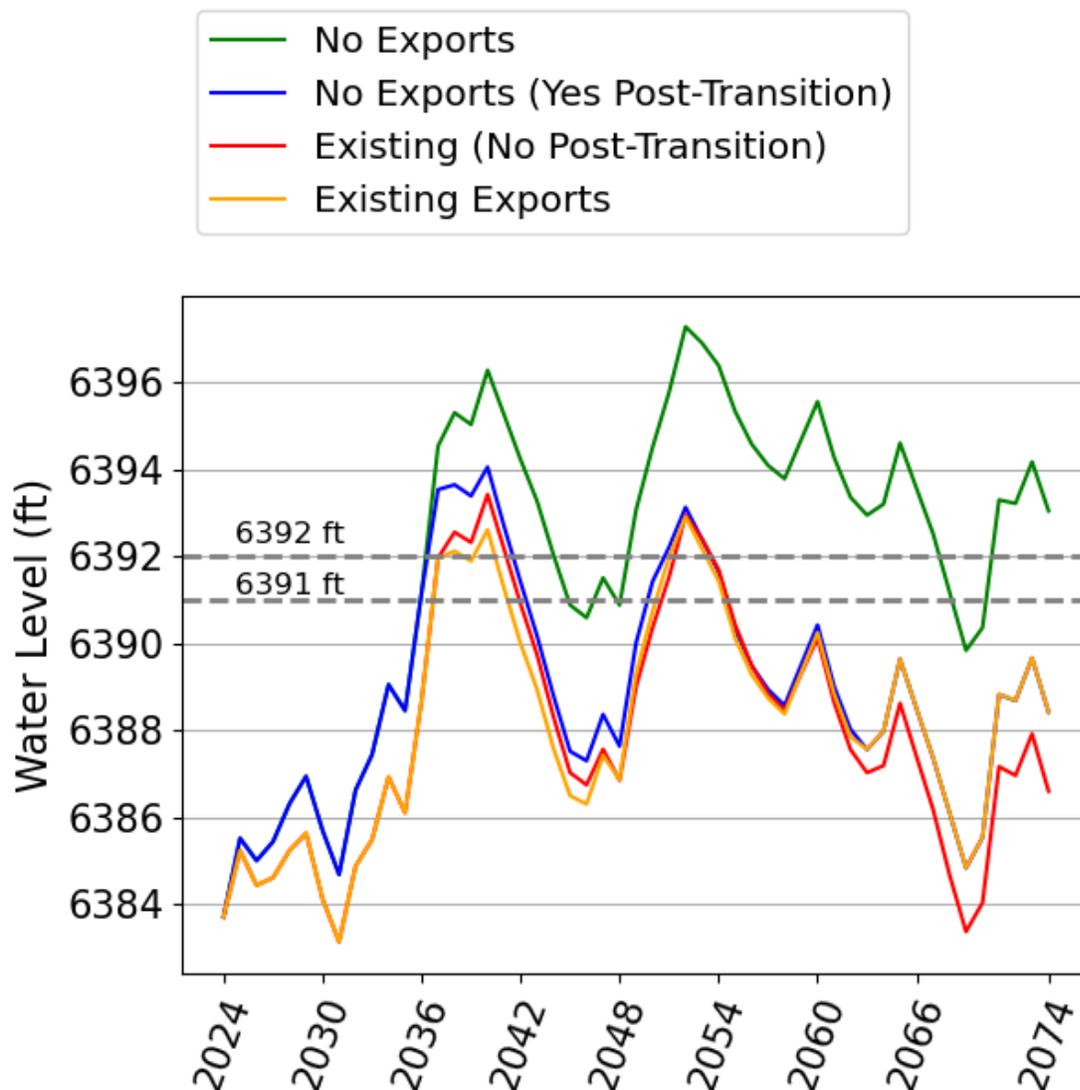
To project future Mono Lake levels, simulations started in 2024 with Mono Lake at 6,383.7 ft (Mono Lake's recorded water level on April 1, 2024). Due to the higher initial water level in 2024 compared to 1994 which was assessed in **Section 4.1.1**, Mono Lake's water level reached the

transition water level for all four export criteria at some point during the simulation (**Figure 4-2**).

While transition exports can raise Mono Lake's water level to 6,391 ft, the post-transition exports fall short of the post-transition D-1631 goal of maintaining a 6,392 ft average. In contrast, No Exports sustains a water level above 6,392 ft for the majority of the simulation. Comparing Existing Exports to No Exports, there is a 6 ft difference by the end of the 50-year simulation (2074).

The differences between the four export criteria (**Table 4-2**) become most apparent once 6,391 ft is reached and the post-transition export criteria becomes relevant. In particular, the importance of the post-transition export criteria is highlighted by comparing No Exports with No Exports (Yes Post-Transition). While No Exports generally leads to a water level greater than 6,392 ft, the No Exports (Yes Post-Transition) scenario results in a water level similar to that under Existing Exports.

For interested readers, additional analysis outlining Mono Lake's water level in response to what's termed the wrapped run method (used in this evaluation) is provided in **Appendix C.1**. The wrapped run method is based on resampling observed weather conditions (fully described in **Appendix A.5**). As such, it does not account for climate change, but it is commonly used by LADWP and MLC to evaluate distinct hydrology conditions in the Vorster and eSTREAM models. This additional analysis is available in the Appendix in response to requests from the MLTWG.

4.1.3 Measuring the Impacts of Future Climate Change

This section includes the first assessment of climate change influence on Mono Lake water level. Simulations of Mono Lake's water level begin in 2024 to demonstrate how Mono Lake's water level may respond to climate change for a recent initial water level. These simulations project how lake levels may change in response to greenhouse gas emissions through 2100. The analyses use 11 GCMs across three emission scenarios (SSP2-4.5, SSP3-7.0, and SSP5-8.5). All SSPs share historical emissions data until 2014, after which their trajectories diverge. As outlined in **Section 3.1.2** SSP2-4.5 and SSP3-7.0 represent more probable futures, while SSP5-8.5 is an extreme scenario with lower likelihood (Huard 2022). A simulation without climate change is also included, where a 34-year period (1955 to 1989) of each GCMs historical conditions is repeated until 2100. For example, conditions from 1955 to 1989 are repeated from 1990 to 2024, 2025 to 2059, and so on. This 1955 to 1989 period was selected as it predates clear climate change signals in the Mono Basin (see **Figure 3-2**).

Figure 4-3 shows how Mono Lake's water level may respond to different emission scenarios (SSPs) with No Exports. By not including exports, this isolates the influence climate change can have on Mono Lake water level. When exports are factored into the modeling, climate change impacts are distributed to both the water level and export amounts (**Appendix Figures C-10, C-11, C-16**). The ensemble mean water level from the 11 GCMs is shown with a 5-year, centered rolling mean to reduce the year-to-year weather variation, or internal-variability, that occurs and can make results more difficult to interpret. Based on this analysis, the impact on lake level from climate change can range from 0 ft to 6.5 ft depending on the emission scenario and

influence of internal variability over the next 75 years, with larger lake level decreases projected as greenhouse gas emissions increase from SSP2-4.5 to SSP5-8.5.

Figure 4-3

Impact of climate change on Mono Lake water level from 2024 to 2100, with a 5-year, centered-rolling average used to reduce interannual variations. Initial water level is reflective of conditions on April 1st, 2024 (6,383.7 ft). Simulation was performed with No Exports. Ensemble mean is shown for interpretation purposes; however, the uncertainty or spread across the GCMs is presented in **Table 4-3***.*
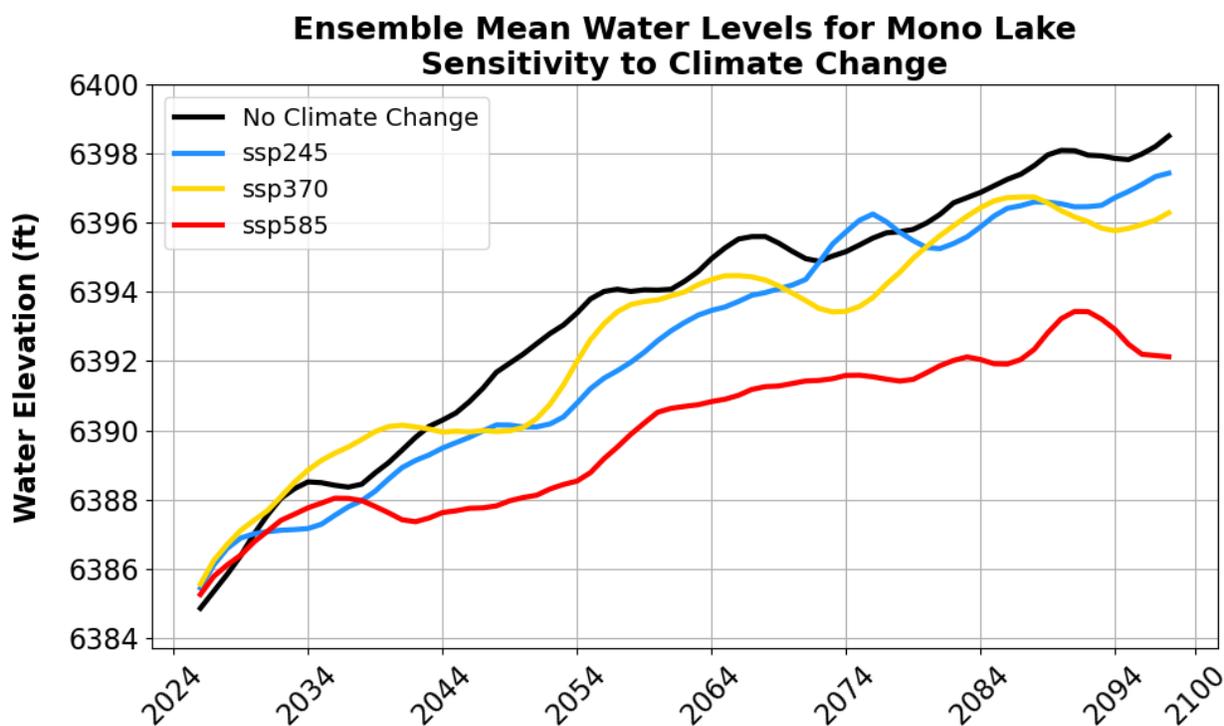
It is important to note that a 5-year rolling period may not adequately remove the impacts of internal variability, meaning that the changes shown in **Figure 4-3** are not exclusively indicative of the long-term climate change signal. For example, while SSP2-4.5 and SSP5-8.5 demonstrate immediately a lower water level compared to the No Climate Change scenario, SSP3-7.0 initially has a higher water level. This appears to be driven by a handful of GCMs with heightened precipitation during this period. Rather than reflecting long-term trends, this could have been caused by a combination of internal-variability and short-term perturbations related to aerosols in SSP3-7.0 (discussed in **Section 3.1.2**; Shiogama et al. 2023). To produce accurate climate change projections, climate science relies on multi-decadal analysis, which usually requires a minimum simulation timeframe of 20 years. As such, timeframes of 20 to 75 years (2044 - 2100) offer the most reliable insights associated with the climate change influence on Mono Lake. More generally, while the ensemble GCM mean is a useful measure of the most likely outcome, it is sensitive to GCMs that have very dry and/or very wet climate signals.

In addition to **Figure 4-3**, which represents the mean or most likely outcome, **Figure C-7** shows the GCMs sorted by their long-term (2024-2100) linear water level trend, from wettest to driest. The spread in GCM projections is largely driven by how each GCM projects precipitation to change across Mono Basin. Such variations in precipitation projections are not uncommon (e.g., Harding et al. 2012) and stems from differences in each GCM's model structure. Each GCM uses distinct assumptions and formulations to simulate atmospheric and oceanic processes. These differences arise from how model developers represent key processes such as sea surface temperature teleconnections, cloud formation, radiation, and convection. Even when refined to accurately represent the current climate, unique internal structures lead to variations in how each GCM responds to changes in greenhouse gas concentrations, resulting in unique projections. For example, some models may simulate stronger or more frequent ENSO events, leading to different precipitation patterns, particularly in regions influenced by ENSO dynamics. While CMIP6 incorporates cutting-edge research from international centers and the filtered list of downscaled CMIP6 GCMs most accurately reflect hydroclimatic conditions relevant to California (Krantz et al. 2021), substantial spread remains in projections of Mono Lake's water levels due to these structural differences between models. Despite the variability in individual GCM outputs, each GCM provides a plausible future. The range of projections provides insights into potential future conditions and helps capture uncertainty across several plausible outcomes. For this reason, the ensemble of downscaled GCMs is evaluated in terms of their agreement on metrics like the likelihood of being at or above 6,391 ft.

The variability across the GCMs projected water levels and the likelihood of being at or above 6,391 ft based on the 11 GCMs (shown graphically in **Figure C-9**) is presented in **Table 4-3** for two time-periods: 30-years from 2024 (2054) and 60-years from 2024 (2084). The likelihood of being at or above 6,391 ft ranges from 71 to 89% for 30 to 60 years from the start of the simulation *without* climate change; however, including climate change results in a 29 to 65% likelihood of being at or above 6,391 ft (a 15 to 42% reduction due to climate change). This clearly demonstrates the impact climate change can have on Mono Lake's water level.

Table 4-3.

Results extracted from the 11 GCMs for each SSP, using a 5-year centered rolling mean of Mono Lake water level results. Simulations were performed with No Exports, and a No Climate Change scenario was included for comparison to the SSP simulations. Table includes results for 30 years from now (2054) and 60 years from now (2084) based on a 2024 initial condition. Table includes the likelihood of Mono Lake's water level being at or above 6,391 ft and the average water level from the 11 GCM projections for each SSP. In addition to the average water level, one standard deviation, based on the water level projections from the 11 GCMs, is included. Likelihood is rounded to the nearest integer.

	No Exports							
	Likelihood >= 6,391 ft (%)				Ensemble Mean Water Level +/- 1 Standard Deviation (feet)			
Year	No Climate Change	SSP 2-4.5	SSP 3-7.0	SSP 5-8.5	No Climate Change	SSP 2-4.5	SSP 3-7.0	SSP 5-8.5
2054	71	56	60	29	6,393.4 +/-3.3	6,390.8 +/-4.0	6,392.0 +/-7.9	6,388.5 +/-5.4
2084	89	64	65	55	6,396.9 +/-4.8	6,395.9 +/-8.6	6,396.4 +/-12.9	6,392.0 +/-10.9

4.1.4 Modeling Export Criteria and Climate Change Impacts on Mono Lake Level

This section assessed Mono Lake's water level when climate change is considered with the four export criteria (**Table 4-2**). **Figure 4-4** shows the water level results for these combinations and the 11 GCMs simulated using the SSP3-7.0 or "business-as-usual" emission scenario from 2024 to 2100. The black line in **Figure 4-4** shows the ensemble mean of the GCMs, which represents the most likely outcome, and the grey shading indicates one standard deviation, representing a portion of the spread or uncertainty across the 11 individual GCM water level projections. This helps capture a portion of the variability among individual GCMs. **Figure C-6** in the Appendix provides results for the other SSPs, with additional detail provided for each individual GCM in **Figure C-7**.

Figure 4-4

*Mono Lake water level projections for SSP3-7.0 in response to the four export criteria (**Table 4-2**). Each of the colored lines represent the 11 GCMs, while the black solid line represents the ensemble mean of the 11 GCMs water level projections. The standard deviation (grey shading) is taken across the water level projections from the 11 GCMs and is a common metric used to represent the spread or uncertainty associated with the GCM projections (IPCC, 2023). The title of each export criteria includes the percentage of GCMs that allow Mono Lake to reach 6,391 ft at some point during the simulation, and the number of GCMs that lead to a positive Mono Lake water level trend from 2024 to 2100.*

78
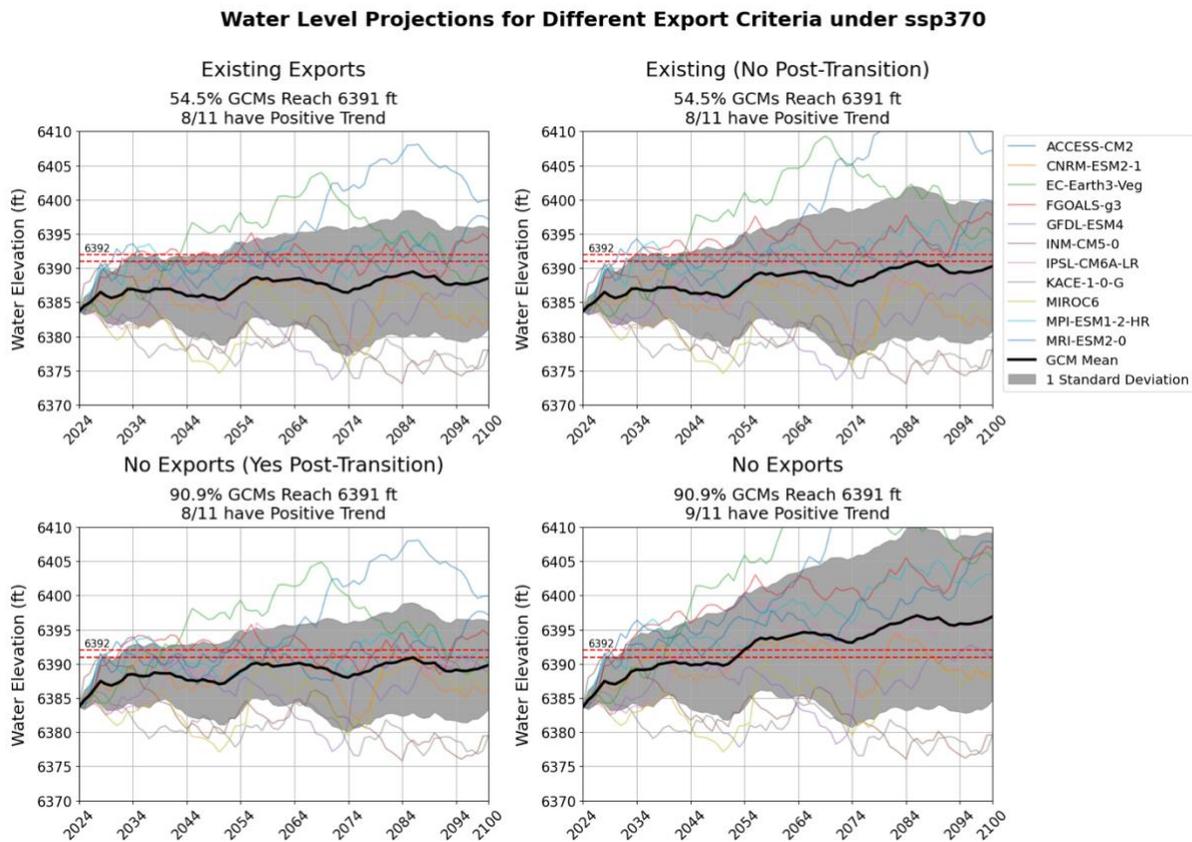
Projected lake levels for each individual GCM are also shown in **Figure 4-4**. Notably, some individual GCMs trend towards wetting conditions and some trend towards drying conditions. The GCMs that project increases in water level represent wetting hydrological conditions (i.e., potentially higher precipitation and runoff), and those that project decreases represent drying conditions (i.e., potentially lower precipitation and runoff). This diverging trend and the large spread in standard deviation reflect uncertainty in GCM projections of Mono Lake precipitation and total runoff across the Mono Basin (**Figure 3-2**), which are driven by differences in precipitation projections (**Figure 3-5**). The long term-trend of each GCM is generally reflective of the response to climate change; however, internal variability can influence annual to multi-annual variations in water level.

While individual GCM projections vary, the ensemble mean water level is highest for No Exports. Only No Exports results in an ensemble mean water level greater than 6,391 ft, which is maintained from roughly mid-century (2050) onward. Under Existing Exports (No Post-Transition) and No Exports (Yes Post-Transition), the ensemble mean Mono Lake water level remains below 6,391 ft for almost the entirety of the 21st century. With No Exports in the transition period, nearly all GCMs (90.9%) reach the 6,391 ft water level at some point from 2024 to 2100, while only 54.5% reach 6,391 ft for the Existing transition export criteria.

Generally, compared to SSP3-7.0, the water level is slightly higher for SSP2-4.5 and noticeably lower for SSP5-8.5 (**Figure C-6, Figure C-8**). However, the three scenarios respond similarly to the existing export criteria. In all cases, including either the existing transition export criteria or the D-1631 post-transition export criteria results in ensemble mean water level projections that remain below the target water level of 6,392 ft. In other words, of the four export criteria, only No Exports leads to a long-term ensemble mean water level at or above 6,392 ft for all three emission scenarios. This suggests that exports lower than the existing D-1631 export criteria will be required to reach an average lake level of 6,392 ft.

While **Figure 4-4** illustrates the most likely water level projection based on the ensemble mean of the 11 GCMs, a probabilistic analysis using the full distribution of individual GCM water levels offers a more robust estimate of the likelihood of future conditions. **Figure 4-5** shows the probability of Mono Lake reaching 6,391 ft and 6,388 ft over time under different SSP scenarios. For each export criteria, the percentage of GCMs that reach or exceed a given water level in each year is plotted, using a 5-year centered rolling mean (e.g. 2054 represents the average likelihood from 2052 to 2056) to smooth interannual variability (a version of this figure without the rolling mean is available in the Appendix **Figure C-12**). Wrapped run results (dashed lines), the method commonly used by LADWP and MLC to represent hydrologic variability but not climate change, are included to demonstrate the wrapped run methodology's tendency to overestimate Mono Lake's water level, primarily due to its omission of long-term climate change effects.

Figure 4-5

Percent of GCMs that lead to Mono Lake water level at or above 6,388 ft (top row) and 6,391 ft (bottom row). Results are based on a 5-year centered rolling window to strengthen interpretation from climate change rather than internal variability. Wrapped runs shown as dashed lines and climate projections as solid lines with unique colors for each existing export combination. Left column shown for SSP2-4.5, middle column for SSP3-7.0, and right column for SSP5-8.5 (wrapped run results same for every column).

Likelihood of Mono Lake Being Above Different Water Levels Under Various Export Criteria and SSP Scenarios
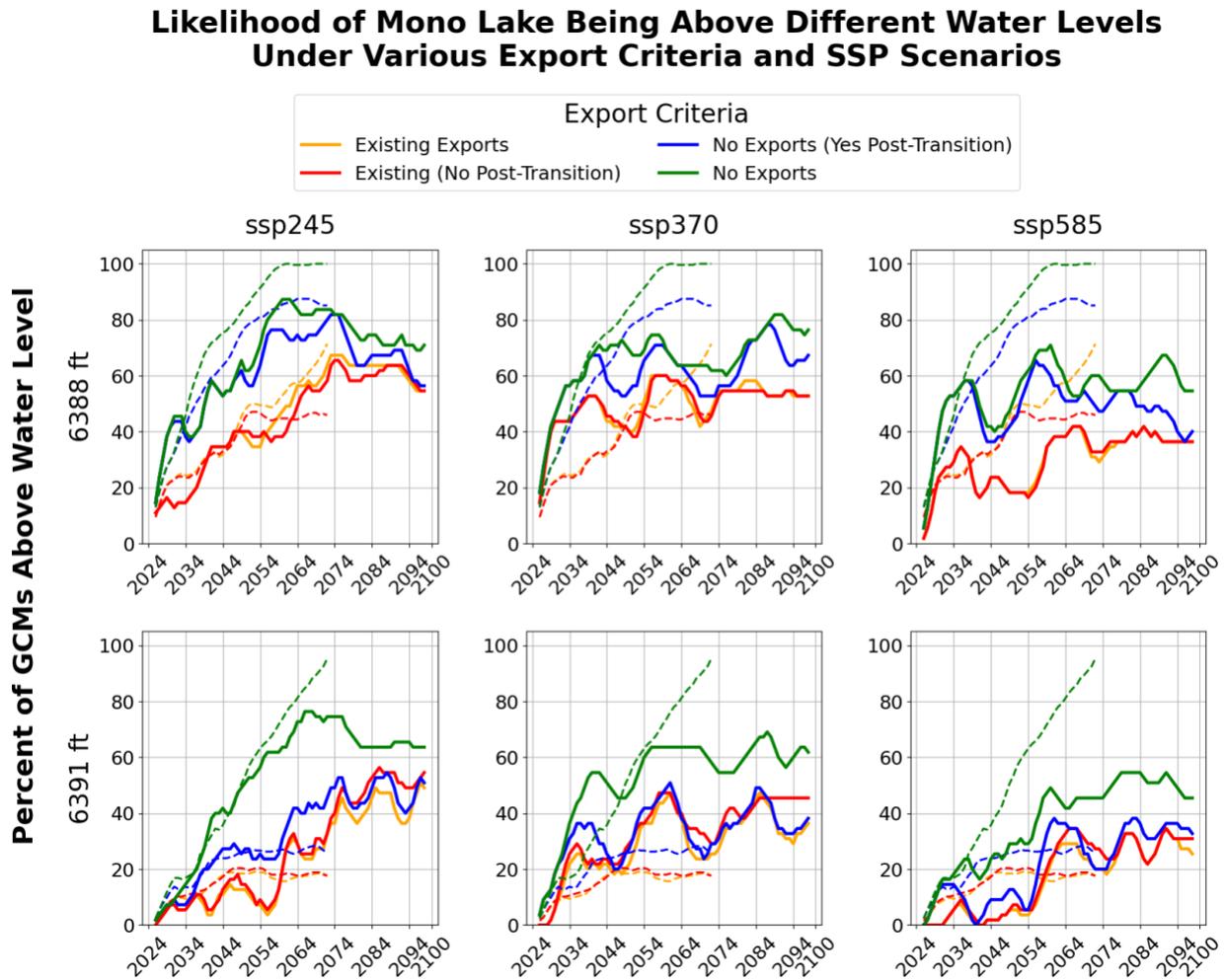
In **Figure 4-5,** No Exports, represented by the solid green line, best illustrates the climate change influence on Mono Lake water level. Also, as previously discussed, it can take several decades for the cumulative effects of climate change and its influence on Mono Lake water level to become apparent. For No Exports, internal variability can account for approximately 35–45% of the variation in water level over the first two decades, but after this period the influence of climate change becomes clearer. For the simulations that include climate change, the likelihood of a water level above 6,391 ft is reduced compared to the wrapped runs. The

impact of climate change is less evident for the other export criteria that include either the existing transition and/or existing post-transition export criteria, which generally exhibit likelihoods similar to the wrapped runs (**Figure 4-5**). This is a result of how the existing transition and post-transition export criteria regulate water level, as evidenced by the larger cumulative exports that occur for lower emission scenarios and the wrapped run approach (**Figure C-11, C-16**). In other words, increases in water level tend to be offset by corresponding increases in exports, as the D-1631 export criteria permit greater exports at higher water levels.

For No Exports, the likelihood of a Mono Lake level above 6,391 ft peaks around 2064 (40 years from start of simulation) and then either remains neutral or decreases. Even at this peak, there is only a 73% to 42% likelihood of being at or above 6,391 ft for SSP2-4.5 and SSP-5.8.5, respectively (**Table 4-4**).

As expected, there are generally lower likelihoods of Mono Lake water level above 6,391 ft for export criteria that include the existing transition and/or post-transition exports as compared to No Exports. For the export criteria that allow existing exports either in the transition or post-transition period, the peak likelihood for a Mono Lake water level above 6,391 ft is delayed substantially (**Figure 4-5**). For Existing Exports, the 2064 likelihood of being at or above 6,391 ft ranges from 29 to 38% for the different emission scenarios considered (**Table 4-4**). **Table 4-4** also includes the cumulative export amounts to highlight the impact of climate change on exports. For example, in addition to SSP5-8.5 resulting in the lowest likelihood of a water level above 6,391 ft, this emission scenario also leads to the lowest amount of exports for the Existing Export criteria.

In **Appendix C.3**, additional analyses are presented to illustrate how climate change affects Mono Lake's water level and export volumes. Specifically, this appendix evaluates how changes in individual hydrologic components influence lake levels. Consistent with the findings in **Section 3.5**, this analysis emphasizes the significant role that increased evaporation plays in lowering Mono Lake's water level. Additionally, this appendix outlines how climate change has influenced Mono Lake water level since 1955.

Table 4-4

Likelihood of Mono Lake water level above 6,391 ft based on 5-year centered rolling mean for No Exports and Existing Exports. Range of results based on SSP2-4.5 and SSP3-7.0. Likelihood is rounded to the nearest integer. 2064 shown since roughly represents the peak likelihood for No Exports, and 2098 represents the last year available from the 5-year rolling mean. Cumulative export amounts are also shown, which are based on the ensemble mean from the 11 GCMs. Bar chart version of this table shown in Figure C-13.

Year	Export Criteria	Likelihood (%)			Cumulative Export Amounts (ac-ft)		
		SSP 2-4.5	SSP 3-7.0	SSP 5-8.5	SSP 2-4.5	SSP 3-7.0	SSP 5-8.5
2064	Existing Exports	29%	38%	29%	570,960	606,838	546,735
2064	No Exports	73%	64%	42%	0	0	0
2098	Existing Exports	49%	36%	26%	1,125,187	1,097,937	998,172
2098	No Exports	64%	62%	46%	0	0	0

4.2   Modeled Mono Lake Levels Using Alternative Export Criteria

This section evaluates the impact of alternative export criteria on the projected future Mono Lake water level from 2024 to 2100. As before, this analysis begins with an initial water level of 6,383.7 ft, representative of April 1, 2024. These alternatives create a spectrum between the four previously assessed export criteria (Table 4-2). While No Exports offers the fastest and highest likelihood of reaching the D-1631 transition water level and maintaining levels at or above 6,392 ft, uncertainty remains about how alternative export criteria could balance water supply exports while supporting increases in Mono Lake's water level in alignment with D-1631 goals. While this report provides a more extensive assessment of transition export criteria options (those in place before reaching 6,391 ft), it also considers a few post-transition export criteria options.

Section 4.2.1 describes the transition export criteria and Section 4.2.2 describes the post-transition export criteria considered in this report. A total of 84 export criteria combinations (14 transition and 6 post-transition criteria) were considered; however, it is important to note that the UCLA-MLM allows for further exploration of various transition and post-transition

strategies, develop custom export criteria to assess and refine different approaches based on various objectives and evolving conditions. **Section 4.2.3** assesses the transition export criteria, followed by an assessment of the post-transition export criteria in **Section 4.2.4**. Isolated assessments of the transition and post-transition export criteria enable a direct evaluation of each period's export criteria. Lastly, **Section 4.2.5** outlines the outcomes when the transition and post-transition export criteria are combined, which would occur in practice as described in D-1631 (SWRCB, 1994).

4.2.1 Modeled Transition Export Criteria Descriptions

While the UCLA-MLM can model countless export criteria, this report focuses on a specific set of transition export criteria proposed during by the MLTWG (A1-A10) and (U1-U4) defined by UCLA CCS (outlined in **Table 4-5)**. As described earlier, the transition export criteria are in effect until 6,391 ft is reached, at which point the post-transition criteria go into and remain in effect.

All export criteria use tiered systems that allow for specific export amounts based on different water level ranges and runoff year types (RYT) (reference **Appendix A.3.2** for description of RYT). For the water level ranges, ending water levels include all decimal values within the specified range. For instance, a range of 6,377-6,379 includes water levels from 6,377.0 up to, but not including, 6,380.0 ft. In addition, a transition export criteria may be static or dynamic. A static export criteria will remain constant until 6,391 ft is reached, which activates the post-transition export criteria. A dynamic export criteria has two or more phases within the transition period, which allows for changes before 6,391 ft is reached. For example, a dynamic export criterion may be set to reduce exports every 10 years until 6,391 ft is reached.

The transition export criteria developed by the MLTWG are referred to as A1-A10, with "A" simply standing for "Alternative". A1 represents the existing export criteria (previously outlined in **Table 4-1a**), A2 represents a no exports criteria, and A8 applies the same rules as the existing post-transition export criteria (previously outlined in **Table 4-1b**) to the transition period. **Table 4-5** provides details on the remaining alternative export criteria. A3, A4, and A6 are static. A5 and A7 are level-dynamic, with changes occurring once a certain water level is reached. A9 and A10 are time-dynamic, with changes occurring after a set number of years.

Table 4-5.

Overview of Transition Export Criteria Evaluated a) designed as part of the Mono Lake Technical Group and b) designed by UCLA-CCS to Demonstrate UCLA-MLM Flexibility (Time Dynamic).

a) *Mono Lake Technical Group Export Criteria*

Transition Export Criteria	Description
A1	Existing
A2	No Exports
A3	No Exports in Wet and Extreme Wet Years
A4	No Exports in Wet-Normal, Wet, and Extreme Wet Years Higher Lake Level Thresholds (6,377 shifted to 6,381 ft, 6,380 shifted to 6,383 ft from existing export criteria)
A5 (Level Dynamic)	**Initial Criteria:** Existing export criteria with A4 lake level thresholds **2nd Criteria (after 6,386 ft is reached):** Increase lake level thresholds by 3 ft (6,381 to 6,384 ft and 6,383 to 6,386 ft)
A6	No exports in Wet-Normal, Wet, and Extreme-Wet Years Exports limited to 4,500 ac-ft from 6,377 to 6,391 ft
A7 (Level Dynamic)	**Initial Criteria:** No exports in Wet-Normal, Wet, and Extreme-Wet Years. Exports limited to 4,500 ac-ft from 6,380-6,383 ft, and 8,000 ac-ft from 6,384-6,391 ft **2nd Criteria (after 6,386 ft is reached):** Increase lake level thresholds (4,500 ac-ft from 6,384-6,385 ft; 8,000 ac-ft from 6,386-6,391 ft)
A8	Existing (Amended Licenses) Post-Transition Criteria 10,000 ac-ft exports from 6,388-6,391 ft, with all water available for exports above 6,391 ft as long as Amended Licenses requirements (Rush Creek SEF) are met.

A9* (Time Dynamic) *Unique from original MLTWG definition*	No exports in Normal, Wet-Normal, Wet, and Extreme-Wet Years **Initial Criteria:** 1,500 ac-ft from 6,383-6,391 ft **2nd Criteria (after first 10 years):** 1,500 ac-ft from 6,383-6,384 ft; 3,500 ac-ft from 6,385-6,391 ft **3rd Criteria (after another 5 years):** 1,500 ac-ft from 6,383-6,387 ft; 3,500 ac-ft from 6,388-6,391 ft
A10 (Time Dynamic)	**Initial Criteria:** 4,500 ac-ft from 6,377 -6,391 ft **2nd Criteria (after 10 years):** 4,500 ac-ft from 6,377-6,379 ft; 16,000 ac-ft from 6,380-6,391 ft **3rd Criteria (after 10 years):** 4,500 ac-ft from 6,377-6,379 ft; 8,000 ac-ft from 6,380-6,391 ft

b) *Export Criteria Defined to Demonstrate UCLA-MLM Flexibility (Time Dynamic)*

Transition Export Criteria	Description
U1	**Initial Criteria:** Outlined in Table 4-6. Note export amounts above 6,391 ft are defined as well (only used when no post-transition export criteria is incorporated) **Dynamic Rules:** Reduce exports by 10% every 5 years until 6,391 ft is reached
U2	**Initial Criteria:** Same as U1 (Table 4-6) **Dynamic Rules:** Shift water level threshold by 1 ft every 5 years until 6,391 ft is reached
U3	**Initial Criteria:** Same as U1 (Table 4-6) **Dynamic Rules:** Shift water level threshold by 1 ft and reduce exports by 10% every 10 years until 6,391 ft is reached
U4	**Initial Criteria:** Same as U1 (Table 4-6)

The additional export criteria (labeled as "U#") were developed by UCLA CCS to demonstrate the flexibility of the UCLA modeling set-up. The "U" is used to distinguish from the A# export criteria and represents "User" defined export criteria that were set-up by UCLA CCS. While the dynamic export criteria in A1-A10 are limited to three phases based on the modeling methods used at the time of their creation, the U1-U4 export criteria were developed to allow for continuous dynamic shifts that occur over specific intervals (e.g. every X number of years). For U1-U4, the same initial export criteria are used (outlined in **Table 4-6**) but with differing dynamic elements established by the unique set of rules outlined in **Table 4-5**.

Table 4-6

Initial export criteria for the user-defined transition export criteria (U1-U4). The ending water level includes all decimal values within the specified range. Greater than 6,391 ft export criteria are only used when a seperate post-transition export criteria is not applied.

Water Level / RYT	Dry	Dry-Normal	Normal	Wet-Normal	Wet	Extreme-Wet
≤6376	0.0	0.0	0.0	0.0	0.0	0.0
6377–6379	4000.0	4000.0	4000.0	0.0	0.0	0.0
6380–6385	6000.0	6000.0	6000.0	0.0	0.0	0.0
6386–6390	10000.0	10000.0	10000.0	0.0	0.0	0.0
6391–6392	12000.0	12000.0	12000.0	0.0	0.0	0.0
6393–6394	16000.0	16000.0	16000.0	8000.0	8000.0	0.0
6395	inf	inf	inf	10000.0	10000.0	0.0

After setting an initial criteria based on allowed exports for different water levels and RYTs (**Table 4-6**), dynamic export criteria like U1-U4 can adjust this criteria over time using the following approaches:

1. **Export Reduction (e.g. U1**): Exports decrease by a set percentage (**W**) every **X** years until the target water level (**Y**) is reached

2. **Water Level Shift (e.g. U2):** The threshold water level range shifts by a set amount (**V**) every **X** years until a target water level (**Y**) is reached.

3. **Combined Adjustment (e.g. U3):** Exports decrease by a set percentage (**W**) and the threshold water level range shifts by a set amount (**V**) every **X** years until the target water level (**Y**) is reached.

4. **Variable Export Reduction (e.g. U4):** Similar to (1), but the export reduction is applied non-linearly based on water levels – Exports decrease by a percentage (**W**) every **X** years until the target water level (**Y**) is reached. W is bigger at lower water levels and smaller at higher levels. A minimum and maximum **W** (e.g., 0% to 20%) are set, representing the range from the lowest export-eligible water level to **Y**.

In these dynamic export criteria, **Y** is the water level that ends the dynamic shift and is typically defined to be the D-1631 transition water level of 6,391 ft. Detailed tables for U3 and U4 water level and RYT shifts are provided in **Appendix D** (**Table D-1** and **D-2**).

4.2.2 Modeled Post-Transition Export Criteria Descriptions

The primary objective of the post-transition export criteria as outlined in D-1631 is to maintain an average water level of 6,392 ft. Previous water budget modeling efforts in D-1631 also indicated that the proposed post-transition export criteria, as defined in **Table 4-1b**, was expected to maintain Mono Lake's water level above 6,390 ft 90% of the time (California State Water Resources Control Board, 1994). As such, post-transition export criteria were assessed in terms of their ability to maintain an average water level around 6,392 ft and assessed based on the percent of time they lead to a water level above 6,390 ft.

This report evaluates six static post-transition (PT) export criteria, including the existing D-1631 criteria, a no-export post-transition scenario, and four user-defined export criteria (PT1-PT4) developed by UCLA CCS (**Table 4-7**). Also, a more detailed table is provided for PT3 (**Table 4-8**), with PT1, PT2, and PT4 available in the appendix (**Tables D-3 to D-5**). The PT1-PT4 post-transition export criteria represent a range of post-transition criteria that were iteratively developed to achieve the post-transition objectives. However, the UCLA-MLM is not limited to these specific export criteria and is capable of modeling countless post-transition export alternatives.

The 14 transition export criteria outlined above (A1-A10 and U1-U4) are evaluated alongside these six post-transition export criteria, resulting in 84 unique export criteria combinations. For clarity, shorthand references are used (e.g., A4+PT3) to denote the combination of transition+ (e.g. A4) and post-transition criteria (e.g. PT3).

Table 4-7

Post-Transition (PT) Export Criteria assessed in this report.

Post-Transition Export Criteria	Description
None	Maintains the existing export criteria at 6,391 ft, including prior reductions in exports or water level modifications. Export amounts for the highest defined water level continue to apply beyond that level. If no export amounts are defined above 6,391 ft (e.g., A1-A10), the export rate from 6,390-6,391 ft remains in effect.
D-1631	Transitions to the existing Amended Licenses post-transition rules (**Table 4-1b**).
PT1	Implements a gradient of exports in the post-transition period (**Table D-3**).
PT2	Prohibits exports below 6,391 ft, allows 4,500 ac-ft/yr during Dry, Dry-Normal, and Normal years between 6,391-6,392 ft, and increases exports from 4,500 to 20,000 ac-ft/yr above 6,393 ft, depending on year type (**Table 4-7**).
PT3	Similar to PT2 but allows unlimited exports above 6,393 ft as long as SEFs are met (**Table D-4**).
PT4	Same as PT3, but the threshold for unlimited exports is lowered to 6,392 ft (**Table D-5**).

Table 4-8

The user-defined post-transition rule referred to as PT3.

Water Level / RYT	Dry	Dry-Normal	Normal	Wet-Normal	Wet	Extreme-Wet
≤6387	0.0	0.0	0.0	0.0	0.0	0.0
6391–6392	4500.0	4500.0	4500.0	0.0	0.0	0.0
6393	inf	inf	inf	inf	inf	inf

The performance of the transition and post-transition are first assessed separately in **Section 4.2.3** and **Section 4.2.4**, respectively. Lastly, **Section 4.2.5** assesses the combined performance of the transition and post-transition criteria, which reflects what would occur in practice based on the protocol outlined in D-1631 (SWRCB, 1994).

4.2.3 Transition Export Criteria Performance

The 14 transition export criteria (**Table 4-5**) were evaluated based on their likelihood of reaching the transition lake level of 6,391 ft. As shown in **Figure 4-6**, the percentage of GCMs that reach 6,391 ft by a given time is key to assessing how different transition export criteria perform. While not every transition criteria is visible in **Figure 4-6** due to overlapping results, details from the figure are extracted and outlined in **Table 4-9**. For transition export criteria with reduced exports compared to the existing criteria, over half of the GCMs can reach 6,391 ft by approximately 2050 for emission scenarios SSP2-4.5 and SSP5-8.5, and as early as 2036 under SSP3-7.0. The earlier transition for SSP3-7.0 may be due to its unique representation of aerosols and the effect this can have on precipitation (discussed in **Section 3.1.2**; Shiogama, 2023).

Generally, the spread between Existing Exports (A1) and No Exports (A2) becomes larger as emissions and time increase, reflecting the combined influence climate change and exports can have on long-term water level conditions. This suggests the transition export criteria can have a stronger influence on Mono Lake's likelihood of reaching 6,391 ft as emissions increase. For example, by 2054 (30 years from the start of simulation) the range between Existing Exports (A1) and No Exports (A2) increases from roughly 27% for SSP2-4.5 to 55% for SSP5-8.5 (**Table 4-9**). For all of the SSPs, there is one GCM that does not reach 6,391 ft by 2100, resulting in a maximum of 90.9% of GCMs reaching the transition water level.

Figure 4-6.

Percent of GCMs that have reached the 6,391 ft over the simulation duration (2024 to 2100). For the A1-A10 as uniquely colored lines, with dashed lines used to distinguish U1-U4. Notably, A2 (no exports) is shown in pink and A1 (existing export criteria) is shown in green. Each column represents a different emission scenario (SSP).

Percent of GCMs that Reach Post-Transition Phase (6,391 ft)
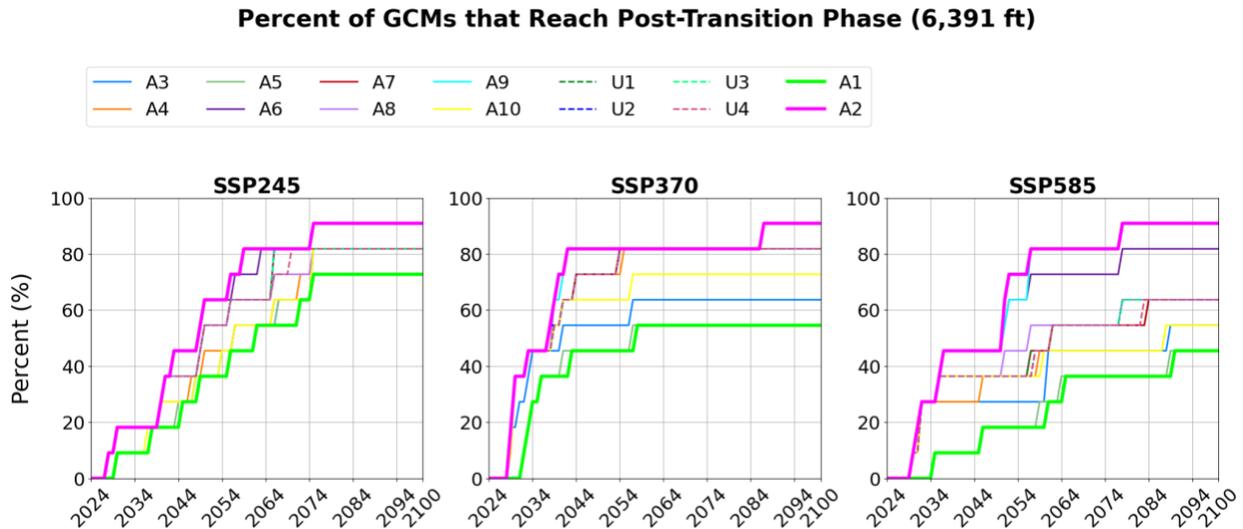
As outlined in **Table 4-9**, by 2054 (30 years from now), export criteria A6 and A9 demonstrate performance comparable to the No Exports scenario across all emission scenarios, while still allowing for limited exports. In contrast, criteria such as A1 (the existing transition export criteria), A3, and A5 generally result in the lowest likelihood of reaching the 6,391 ft threshold. Several other export criteria yield intermediate outcomes, with performance varying by emission scenario. By 2084 (60 years from now), most export criteria evaluated lead to >81.8% likelihood of reaching 6,391 ft aside from A1, A3, A5, and A10 which demonstrate reduced likelihoods.

Table 4-9

For different transition criteria, the percent of GCMs that have reached the 6,391 ft transition water level at any point from 2024 to 2054 (up to 30 years from start of simulation) and from 2024 to 2084 (up to 60 years from start of simulation). Note, this is only a measure of whether 6,391 ft is reached during each time-frame of interest, and the post-transition export criteria has no impact on the results in this table. Greener colors indicate a higher percentage of GCMs that reached the threshold, while redder colors indicate a lower percentage. Coloring in the leftmost column is based on the average across all emission scenarios and both time-frames considered.

	2024 to 2054			2024 to 2084		
	ssp245	ssp370	ssp585	ssp245	ssp370	ssp585
A1 (43.9%)	36.4	45.5	18.2	72.7	54.5	36.4
A2 (80.3%)	63.6	81.8	72.7	90.9	81.8	90.9
A3 (51.5%)	36.4	54.5	27.3	81.8	63.6	45.5
A4 (63.6%)	45.5	72.7	36.4	81.8	81.8	63.6
A5 (45.5%)	45.5	45.5	18.2	72.7	54.5	36.4
A6 (75.7%)	63.6	81.8	63.6	81.8	81.8	81.8
A7 (66.6%)	54.5	81.8	36.4	81.8	81.8	63.6
A8 (68.2%)	54.5	81.8	45.5	81.8	81.8	63.6
A9 (77.2%)	63.6	81.8	63.6	81.8	81.8	90.9
A10 (57.6%)	45.5	63.6	36.4	81.8	72.7	45.5
U1 (66.6%)	54.5	81.8	36.4	81.8	81.8	63.6
U2 (66.6%)	54.5	81.8	36.4	81.8	81.8	63.6
U3 (66.6%)	54.5	81.8	36.4	81.8	81.8	63.6
U4 (66.6%)	54.5	81.8	36.4	81.8	81.8	63.6

4.2.4 Performance of the Post-Transition Export Criteria Considered

Table 4-10 displays the performance for the six post-transition export criteria (None, D-1631, PT1-PT4) based on their ability to meet the two post-transition objectives previously described. Similar to previous simulations, a start year of 2024 is used with the 6,383.7 ft (April 1st, 2024) water level as an initial condition. Since this section focuses on post-transition conditions, A2 (No Exports) is used as the transition criteria, as it results in the highest number of GCMs reaching 6,391 ft and increases the time spent in the post-transition period. This ensures the largest possible sample size for assessing post-transition conditions, while using an initial water level condition reflective of present-day conditions. Under the different emission scenarios, 10 out of 11 of the GCMs (90.9%) transition (reach 6,391 ft). To concentrate on post-transition performance, statistics in **Table 4-10** are reported based on water level conditions only after the post-transition period begins. The statistics reported in **Table 4-10** are shown graphically in the appendix (**Figure D-1**).

Table 4-10

Overview of post-transition performance. Simulation was performed with an initial water level of 6383.7 ft and no exports (A2) in the transition period, but statistics are reported based on water level conditions only after 6,391 ft is reached (when the post-transition period begins). Ensemble mean from the 11 GCMs shown for each SSP, along with one standard deviation based on the range of outcomes from the 11 GCMs. Table reports the primary objective outlined in D-1631, which is to maintain an average water level of 6,392 ft in the post-transition period. Also, the percentage of time the water level is above 6,390 ft is included as this metric was also assessed in D-1631.

SSP Post Transition Export Criteria	% Time Above 6390 Post-Transition (Mean ± Std)			Average Water Level Post-Transition (Mean ± Std)		
	ssp245	ssp370	ssp585	ssp245	ssp370	ssp585
D_1631	59.8 ± 29.0	54.5 ± 33.8	44.4 ± 40.3	6390.5 ± 3.0	6390.4 ± 4.5	6389.3 ± 5.7
None	79.5 ± 31.9	70.4 ± 36.5	61.1 ± 43.8	6395.1 ± 4.9	6395.3 ± 7.9	6392.7 ± 8.2
PT1	76.0 ± 32.7	68.4 ± 36.5	55.7 ± 41.6	6392.8 ± 3.9	6392.7 ± 6.0	6391.0 ± 7.0
PT2	77.2 ± 32.7	69.3 ± 36.2	57.0 ± 41.9	6393.0 ± 3.9	6393.0 ± 6.1	6391.2 ± 7.0
PT3	74.3 ± 32.4	68.4 ± 35.5	56.0 ± 41.0	6391.9 ± 3.2	6391.7 ± 4.7	6390.4 ± 5.8
PT4	71.5 ± 32.1	65.8 ± 34.6	54.8 ± 40.3	6391.4 ± 3.1	6391.3 ± 4.5	6390.2 ± 5.6

For the more likely SSPs (SSP2-4.5 and SSP3-7.0), no exports in the post-transition period (labeled "None" in **Table 4-10**) results in an average percentage of time spent above 6,390 ft between 70.4% to 79.5% and an average water level of roughly 6,395.2 ft. In comparison, the existing post-transition criteria (D-1631) reduces the ensemble mean average water level to roughly 6,390.5 ft and the average percentage of time the GCMs spend above 6,390 ft is reduced to between 54.5% and 59.8%.

When no exports are allowed during the post-transition period, Mono Lake's ensemble mean average water level remains above 6,392 ft. While the ensemble mean represents the most likely outcome, this does not guarantee that Mono Lake's water level, even without post-transition exports, will stay above this threshold. The standard deviation, calculated based on the spread of individual GCM projections (e.g. **Figure 4-4**), highlights the considerable uncertainty associated with Mono Lake's future water level due to variability in projected hydrologic conditions (e.g. precipitation, and runoff patterns shown in **Figure 3-2, Figure 3-5**). While a portion of individual GCMs exhibit long-term increases in water level, others exhibit neutral or even decreasing water level trends (e.g. **Figure 4-4, Figure C-7**). This suggests that Mono Lake's water level may or may not exceed the 6,392 ft threshold even without exports.

As indicated by the standard deviation of the average post-transition water level in **Table 4-10**, there is a reduction in uncertainty for the post-transition water level when post-transition exports are allowed. Because the tiered exports are dependent on lake level, these controlled water withdrawals (exports) tend to stabilize natural fluctuations. For example, when the lake level is high enough to permit exports, excess water is removed, preventing extreme increases in the water level during wetter periods. This creates a buffering effect that narrows the range of possible lake levels. In contrast, when exports are not allowed, the lake is more susceptible to the full range of potential climate outcomes, leading to greater uncertainty and larger fluctuations. This is reflected in the water budget model results, where the standard deviation of post-transition water level is significantly larger for the no export post-transition criteria (ranging from approximately 4.9 to 7.9 ft) compared to the existing post-transition export criteria (3 to 4.5 ft) for SSP2-4.5 and SSP3-7.0.

Based on the most likely outcome (GCM ensemble mean) and the more likely emission scenarios (SSP2-4.5 and SSP3-7.0), the post-transition export criteria that comes closest to achieving a long-term average water level of 6,392 ft while allowing for exports is PT3 (**Table 4-10**). PT3's average water level for SSP2-4.5 and SSP3-7.0 is roughly 6,391.8 ft. Under PT3, the percentage of time water levels are above 6,390 ft is only reduced by roughly 2% to 5% relative to no exports (rather than 26 to 30% for the existing post-transition criteria). The average post-transition water level under PT3 is also associated with a decrease in uncertainty compared to the no export scenario.

Based on its effectiveness in achieving post-transition objectives, PT3 was selected for more detailed analysis with the transition export criteria in the subsequent section. However, the existing post-transition export criteria (D-1631) is included for reference.

4.2.5 Performance of Transition and Post-Transition Export Criteria

In previous sections, the transition and post-transition export criteria were evaluated independently. This approach enabled a direct assessment of each period's export criteria without introducing compounding effects from their interaction. It provided valuable insights—for example, it highlighted how reducing transition exports can increase the likelihood of lake levels reaching 6,391 ft, and it helped identify a post-transition criterion, like PT3, that performs well in achieving long-term target water level objectives. However, under the D-1631

framework, transition and post-transition criteria must work in sequence to facilitate an average lake level of 6,392 ft. Therefore, this section evaluates likelihood of being at or above 6,391 ft based on analysis of both transition and post-transition export criteria. To provide a more practical assessment, export criteria are applied as they would be in practice under D-1631 guidance: transition export criteria are in effect until 6,391 ft is reached, after which post-transition criteria remain in place.

While **Figure 4-6** focused on the transition criteria by showing the percentage of GCMs that reach 6,391 ft at any point between 2024 to 2100, **Figure 4-7** in this section shows the percentage of GCMs at or above 6,391 ft for each year throughout the 2024 to 2100 simulation period. This provides a more continuous survey of Mono Lake conditions and the combined influence of transition and post-transition export criteria. The likelihood of being at or above 6,391 ft is the focus of this section since it provides a reference that is relevant to both the transition and post-transition objectives. As outlined previously, 6,391 ft is the threshold for shifting to the post-transition period, and it provides a close reference to the post-transition objective of maintaining an average water level of 6,392 ft. Generally, there is roughly a 5% reduction in the likelihood of being at or above 6,392 ft as compared to 6,391 ft (**Figure C-12**).

Figure 4-7 includes the 14 transition export criteria from **Table 4-5** and compares two post-transition export criteria: (a) the D-1631 criteria (**Table 4-2b**) and (b) the PT3 criteria (**Table 4-8**). For context, **Figure 4-7** also includes the two book-end export criteria, No Exports (A2+None) and Existing Exports (A1+D-1631) in each plot. For this analysis PT3 post-transition criteria is chosen for its relatively reliable performance, specifically its ability to balance post-transition objectives with allowed exports; however, further analysis of other post-transition criteria is provided in **Appendix D**. In addition, as discussed in **Section 5**, interested parties may also have the ability to develop and assess additional transition and post-transition export criteria combinations with the UCLA-MLM User Interface.

As shown in **Figure 4-7a**, after roughly 10 years the Existing export criteria (A1+D-1631) reduces the likelihood of remaining above 6,391 ft by approximately 20–30% compared to No Exports (A2+None). With the PT3 post-transition export criteria (**Figure 4-7b**), the likelihood of being at or above 6,391 ft increases for all transition strategies, which reflects the benefit of the PT3 post-transition criteria. Notably, a few transition strategies (e.g. A6, A9), when combined with the PT3 post-transition criteria, can achieve outcomes close to No Exports (A2+None).

Figure 4-7.

Percent of GCMs (likelihood) with projected water level above 6,391 ft. To reduce year-to-year variability, the 5-year centered rolling window is shown. ***a)*** *Top row is based on simulations with the D-1631 post-transition export criteria, and* ***b)*** *bottom row is based on the PT3 post-transition export criteria. For reference, book-end export criteria for No Exports is included as a black line (A2+None) and the existing export criteria is included as a red line (A1+D-1631). These book-end exports represent the lowest and highest likelihood for being at or above 6,391 ft.*
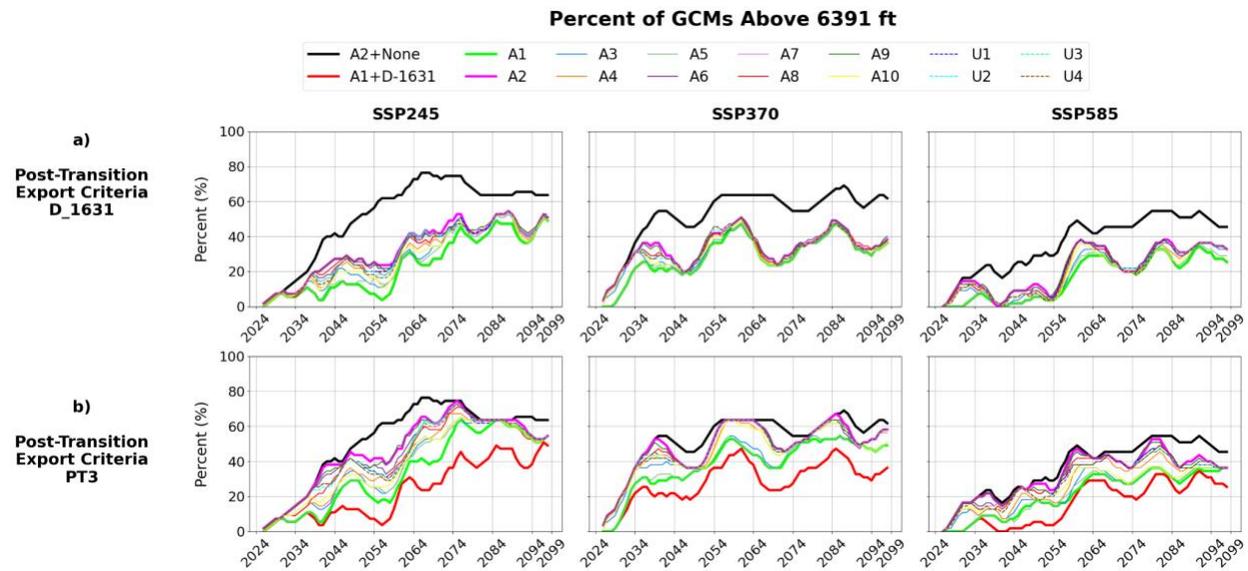

Table 4-11 provides a comparison of PT3 performance when paired with different transition export criteria by outlining the likelihood of being at or above 6,391 ft for two time-frames: 30 years (2054) and 60 years (2084) from the start of the simulation. The two book-end export criteria are also included, denoting the highest likelihood for a water level above 6,391 ft, which is achieved with No Exports (A2+None), and the lowest likelihood which is achieved with the Existing export criteria (A1+D-1631). In between these, the PT3 post-transition export criteria allows for a range of outcomes depending on the transition export criteria applied. Generally, differences between transition export criteria are more apparent in the near future (e.g. 30 years from now rather than 60 years from now), when a greater portion of GCMs are still in the transition period. However, further into the simulation (e.g. 60 years into the simulation) more GCMs reach the post-transition period where PT3 is universally applied, which reduces differences in results between the transition export criteria.

By 2054, or 30 years from the start of simulation, only No Exports (A2+None) allows for a likelihood of being at or above 6,391 ft that is greater than 50% for SSP2-4.5 and SSP3-7.0. Despite demonstrating below a 50% likelihood of being at or above 6,391 ft, the following transition export criteria, when coupled with PT3, allow for a relatively high likelihood of being at or above 6,391 ft by 2054: A2, A6, and A9. By 2084, or 60 years from the start of simulation,

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a likelihood of being at or above 6,391 ft greater than 50% is achieved for all of the transition export criteria combined with PT3 for SSP2-4.5 and SSP3-7.0. However, the likelihood of being at or above 6,391 ft remains below 50% for all transition combinations with PT3 for the highest emission scenario (SSP5-8.5). Generally, differences between transition export criteria when coupled with PT3 are relatively small 60 years into the simulation (by 2084), while differences between post-transition export criteria (e.g. A1+D-1631 compared to A1+PT3) become more apparent.

Table 4-11

Likelihood of projected water level above 6,391 ft for two time-frames: 30 years from the start of the simulation (2054) and 60 years from the start (2084). Based on a 5-year, centered rolling window means to reduce year-to-year variability. Greener colors indicate a higher percentage of GCMs that are at or above 6,391 ft, while redder colors indicate a lower percentage. Coloring in the leftmost column is based on the average across all emission scenarios and both time-frames considered.

	2054			2084		
	ssp245	ssp370	ssp585	ssp245	ssp370	ssp585
A2+None (54.8%)	56.4	60.0	29.1	63.6	65.5	54.5
A1+D_1631 (27.6%)	7.3	36.4	3.6	45.5	45.5	27.3
A1+PT3 (36.4%)	18.2	40.0	14.5	61.8	52.7	30.9
A2+PT3 (48.2%)	41.8	52.7	23.6	63.6	65.5	41.8
A3+PT3 (38.5%)	25.5	41.8	16.4	63.6	52.7	30.9
A4+PT3 (42.7%)	29.1	47.3	16.4	63.6	61.8	38.2
A5+PT3 (38.2%)	25.5	41.8	14.5	63.6	52.7	30.9
A6+PT3 (47.2%)	38.2	52.7	21.8	63.6	63.6	43.6
A7+PT3 (46.3%)	34.5	52.7	21.8	63.6	63.6	41.8
A8+PT3 (46.0%)	34.5	52.7	21.8	63.6	61.8	41.8
A9+PT3 (47.2%)	38.2	52.7	21.8	63.6	63.6	43.6
A10+PT3 (41.2%)	25.5	45.5	20.0	63.6	61.8	30.9
U1+PT3 (46.6%)	34.5	52.7	21.8	63.6	63.6	43.6
U2+PT3 (46.0%)	34.5	52.7	20.0	63.6	63.6	41.8
U3+PT3 (45.7%)	32.7	52.7	20.0	63.6	63.6	41.8
U4+PT3 (46.0%)	32.7	52.7	20.0	63.6	63.6	43.6

4.3 Ongoing Export Criteria Research

UCLA CCS has expanded the evaluation of alternative export criteria to include 50,000 transition criteria combined with three post-transition criteria (D-1631, None, and PT3). This was performed to further explore a fuller scope of possible alternative transition export criteria. Further development of simulations and analysis is ongoing, and updated findings will be provided to the SWRCB and documented in an academic journal.

This assessment used static transition criteria and a limited set of three post-transition criteria due to computational constraints. The UCLA-MLM runs quickly for a small number of criteria, taking seconds for a single export criteria and up to a few minutes for ten to a hundred export criteria, but evaluating 50,000 transition criteria requires approximately 30 hours per post-transition criterion across three SSP scenarios. Given this computational demand, analyses focus on SSP2-4.5 and SSP3-7.0, as SSP5-8.5 represents an extreme scenario with lower likelihood. The primary post-transition criterion assessed is PT3, which generally meets post-transition expectations, though D-1631 and the absence of a post-transition criterion (None) are also included for comparison. Additional post-transition criteria that align with post-transition goals can be explored in future analysis.

Given computation limits, an assessment was performed for a transition criteria population space based on the following combinations of exports for different water level thresholds and RYTs:

Export Amounts (ac-ft): 0, 4500, 9000, 13500, 16000

Runoff Year Types: Dry (includes Dry, Dry-Normal, Normal) and Wet (includes Normal-Wet, Wet, Extreme Wet)

**Water Level Ranges (ft):** [6,377-6,380], [6,381-6,385], [6,386-6,390], [6,391 and above]

As in the previous alternatives analysis, the ending water level includes all decimal values within the specified range. For example, a range of 6,377-6,380 ft represents levels from 6,377.0 up to 6,380.999 ft but excludes 6,381 ft. Below 6,377.0 ft, exports are set to zero ac-ft. Above 6,391 ft, the post-transition criteria take effect for the existing (D-1631) and user-defined (PT3) post-transition criteria. When no post-transition criterion is applied (None), use of transition export criteria continues.

The export criteria structure is designed to vary exports based on water level and runoff year type (RYT) using four water level thresholds and two RYTs (dry and wet). Exports are allowed to vary between five possible values for each combination of water level range and RYT, leading to 390,625 total scenarios (5 export values across 8 water level and RYT combinations). When combined with three post-transition criteria (D-1631, None, PT3), the total expands to 1,171,875 export criteria combinations. To ensure a feasible computation time of roughly 72 hours, the 390,625 transition possibilities were reduced to 50,000 transition criteria.

Figure 4-8 illustrates the likelihood (percentage) of GCMs projecting a water level above 6,391 ft over three time periods (1-15, 15-30 and 30-45 years from 2024) for the 50,000 sampled transition export criteria. The analysis includes three post-transition export criteria (D-1631, None, PT3) and two climate scenarios (SSP2-4.5 and SSP3-7.0). Additionally, the transition criteria previously assessed that were developed as a part of the MLTWG (Table 4-5) are included for reference. The figure uses color to represent the likelihood of exceeding 6,391 ft for each export criteria, while the axes display the average dry and wet year exports allowed over the specified time ranges. The plotted export amounts are based on the average exports during each time-frame for the 11 GCMs. The results highlight the range of impacts different transition and post-transition exports have on the likelihood of Mono Lake's water level at or above 6,391 ft.

Figure 4-8

Evaluation of percentage of GCMs that are above 6,391 ft (the likelihood) during different time-ranges (1-15, 15-30 and 30-45 years from 2024) for the 50,000 transition export criteria that were sampled. Includes results for three post-transition export criteria (D-1631, None, PT3) and SSP2-4.5 and SSP3-7.0. The colors in the figure reflect the percentage likelihood for being at or above 6,391 ft for each export criteria, and the axes show the average dry (x-axis) and wet (y-axis) year export amounts for each export criteria (across the time range considered and the 11 GCMs).
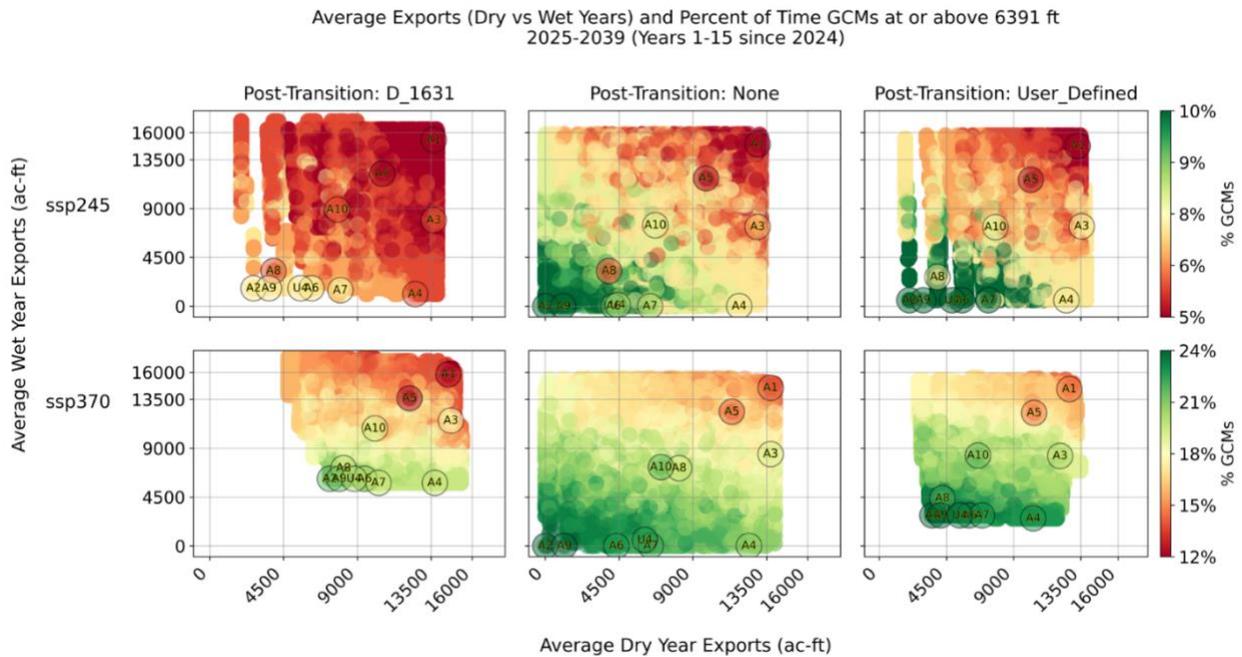
Average Exports (Dry vs Wet Years) and Percent of Time GCMs at or above 6391 ft
2039-2054 (Years 15-30 since 2024)
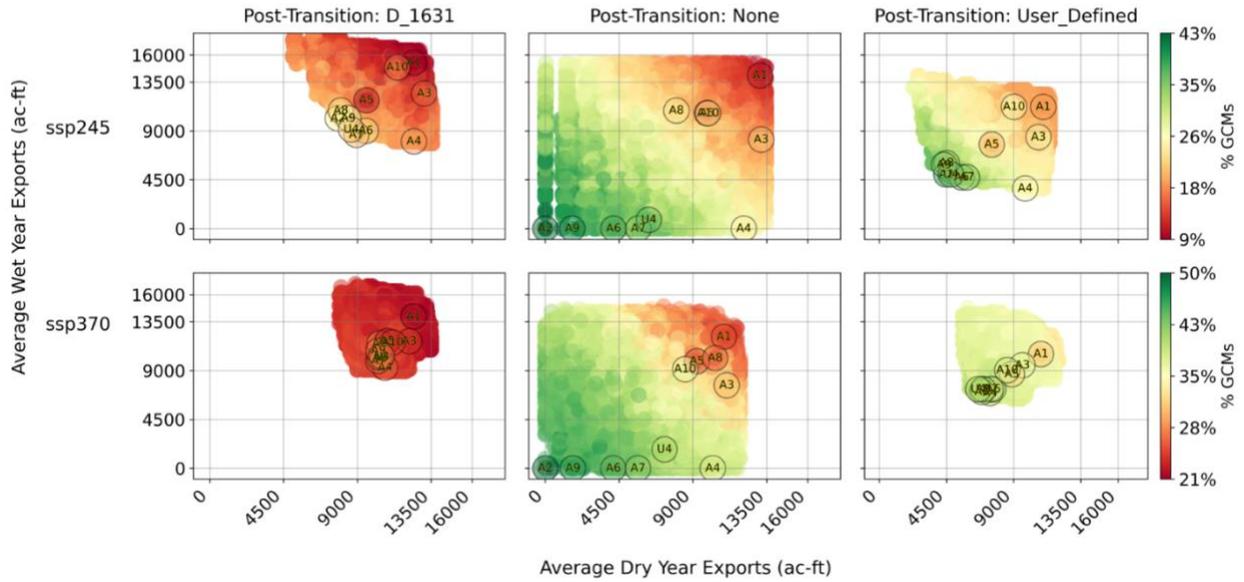
Average Exports (Dry vs Wet Years) and Percent of Time GCMs at or above 6391 ft
2054-2069 (Years 30-45 since 2024)
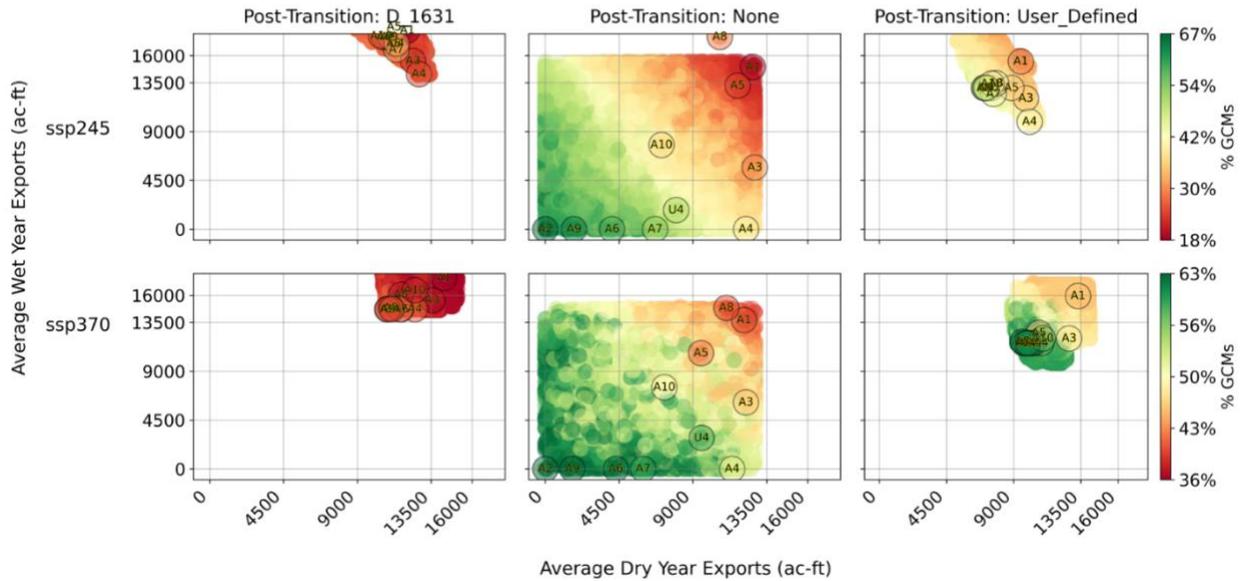
In this analysis, the PT3 post-transition export criteria consistently outperforms the existing D-1631 export criteria in supporting a Mono Lake water level above 6,391 ft. In earlier years, transition export criteria have a larger role in determining the likelihood of being at or above 6,391 ft and the averaged export amounts, while post-transition export criteria became more influential over time. PT3 offers a significantly higher likelihood of being at or above 6,391 ft compared to D-1631, particularly 30 to 45 years from now. Under the D-1631 post-transition export criteria, most transition export criteria result in a low probability of maintaining a water level above 6,391 ft after 15 years. In contrast, PT3 maintains a higher likelihood of being at or above 6,391 ft over the long term, particularly with transition export criteria that allow for lower exports. The increased likelihood of being at or above 6,391 ft under PT3, requires an average export reduction after 15 years of approximately 1,000 to 4,500 ac-ft/yr during wet and dry years compared to the D-1631 post-transition export criteria, though this varies by emission scenario and transition export criteria.

The alternative transition export criteria (A1-A10, U1-U4) represent a variety of different strategies which represent a spectrum of ways to balance exports with lake recovery. These alternatives are also included in **Figure 4-8**, to provide insight into their performance within a more complete scope of possible outcomes. When combined with PT3, static export criteria, like A6, and dynamic approaches, such as A7 and U1-U4, can sustain roughly a 35% likelihood of being at or above 6,391 ft within 15-30 years and roughly a 60% likelihood of being at or above 6,391 ft within 30-45 years while still permitting dry year exports. In contrast, these same criteria combined with the D-1631 post-transition exports leads to less than a 28% likelihood of being at or above 6,391 ft within 15-30 years, and less than a roughly 40% likelihood of being at or above 6,391 ft within 30-45 years.

Figure 4-8 illustrates the sensitivity of Mono Lake's water level being at or above 6,391 ft to a gradient of 50,000 transition export criteria. The results suggest that other export criteria may achieve a similar balance of exports and likelihoods of being at or above 6,391 ft as A6, A7, A9, and U1-U4. While **Figure 4-8** provides a broad overview, detailed analyses of individual export criteria, such as that shown in **Figure 4-7**, are necessary to assess how slight export criteria modifications influence Mono Lake's ability to be above 6,391 ft.

5 FUTURE WORK

This section describes ongoing efforts to expand the application and analytical use of the UCLA-MLM. Planned activities include development of a user interface and continued research to evaluate a broader range of export scenarios. Together, these efforts are intended to support continued analysis and informed decision-making under evolving climate and management conditions.

5.1   UCLA-MLM Access

The UCLA-MLM was delivered to the SWRCB in 2025 and is being maintained as a technical modeling tool to support ongoing analysis. As previously mentioned, the UCLA MLM is a complex, technical tool that incorporates climate projects and detailed hydrologic processes. It was developed for use by scientists, engineers, and water-management professionals with experience in climate and hydrologic modeling and familiarity with the broader ecological challenges facing Mono Lake. As such, the model is not intended for general public use or simplified interpretation. To support transparency and understanding, summaries and key findings are provided to explain what the model shows and how it informs management decisions.

The UCLA MLM is accessed through a User Interface, which will be made available to interested parties by request. The SWRCB may also coordinate sessions to demonstrate UCLA-MLM use and functionality.

For informational purposes, a brief summary of the User Interface is provided in this section. The User Interface will provide an interactive platform that allows for independent evaluation of a wide range of export criteria beyond just those examined in this report.

5.2   UCLA-MLM Interface Overview

The UCLA-MLM includes a python-based User Interface that allows users to define and simulate both transition and post-transition export criteria. Although the underlying computer code is written in python, the User Interface was developed to enable users without programming experience to operate the UCLA-MLM. Through the User Interface, users will be able to configure customized simulations such as:

⇒ Initial water level (ft above sea level)
⇒ Climate Projections or Wrapped Run Method
⇒ Simulation period:
  • can range from 1955 to 2099 for Climate Projections
  • can range from 1955 to 2020 for Wrapped Run method
⇒ Emission scenarios including 11 GCMs each: SSP2-4.5, SSP3-7.0, and/or SSP5-8.5
  • only applies for climate projections (not wrapped run method)
⇒ List of transition export criteria
  • Pre-Defined options such as Existing Exports and No Exports
  • However, user can create additional static or dynamic options
⇒ List of post-transition export criteria
  • Pre-Defined options such as D-1631 and None
  • However, user can create additional options

This set of options is demonstrated in **Figure 5-1**, which provides a screenshot from a prototype version of the User Interface. Note, simulations ending in 2099 from climate projections will produce a lake level for the year 2100, and simulations ending in 2020 for the wrapped run method will produce a lake level for the year 2021.

Figure 5-1

Screenshot from prototype-version of the UCLA-MLM User Interface. This screenshot is from the portion of the User Interface that asks for users to define simulation conditions.

Clicking ▶ symbol below will provide list of user options. After desired options are selected, continue to next step.

▶ Show code

···

6383.7

Initial Water Level set to: 6383.7

Wrapped or Projections:

Wrapped
Projections

Select Start and End Year for Projections:

Years available: 1955-2099, where end year predicts following years April 1st water level

Start Year: 2024

End Year: 2099

Emission Scenario Options (only relevant for projections)

Select All	Deselect All

☑ ssp245
☑ ssp370
☑ ssp585

Selected Emission Scenario Options (only relevant for projections): ['ssp245', 'ssp370', 'ssp585']

Transition Export Criteria

Select All	Deselect All

☑ A1
☑ A2
☐ A3
☐ A4
☐ A5
☐ A6
☐ A7
☐ A8
☐ A9
☐ A10

Selected Transition Export Criteria: ['A1', 'A2']

Users may choose from the pre-loaded export criteria or define new ones. Transition criteria can be either static (single phase) or dynamic. Dynamic transition criteria allow for multiple phases that adjust export amounts based on time or lake level thresholds. Each phase requires that the user defines water level thresholds and export amounts for each water year type (RYT).

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Figure 5-2 presents a prototype from the User Interface that shows how a user develops a transition export criteria. The shown setup uses a dynamic transition criteria, which shifts to a new export criteria after a user-defined number of years or once a specific water level is reached. Post-transition export criteria follow the same set-up as **Figure 5-1**, except that only a single phase can be defined.

Figure 5-2

Prototype of the User Interface that allows a user to define export criteria. Shown below for an example transition export criteria. Different water level thresholds are defined, with different export amounts allowed for each water level threshold. Users must define the export amounts allowed for each runoff year type (Dry to Extreme-Wet).

Figure 5-3 provides a screenshot from the User Interface of a transition export criteria. Users can iteratively refine (e.g. as outlined in **Figure 5-2**) and view the export criteria before adding it to the list of export criteria available for assessment in the User Interface.

Figure 5-3

Example export criteria developed from the prototype version of the User Interface. Note, for the water level range in Phase 1: 6,382 to 6,384, this includes all water levels from 6,382.0 to 6,384.99 ft (if 6,385 ft reached then export amounts are based on the 6,385 to 6,390 range). The 6,391 ft export amount applies at and above 6,391 ft and is only used if "None" is selected as the post-transition export criteria. This example includes a second phase that begins after 10 years (as indicated at the bottom of the figure by 'Dyn_Type': 'year' and 'Phase_Thresh': [10.0]).

```
'Phase: 1'
Water Level / RYT      Dry  Dry-Normal  Normal  Wet-Normal      Wet  Extreme-Wet

    ≤6375–6382         0.0         0.0     0.0         0.0      0.0          0.0

    6382–6385       3000.0      3000.0  3000.0      3000.0   3000.0       3000.0

    6385–6391       9000.0      9000.0  9000.0      9000.0   9000.0       9000.0

      ≥6391        12000.0     12000.0 12000.0     12000.0  12000.0      12000.0
'Phase: 2'
Water Level / RYT      Dry  Dry-Normal  Normal  Wet-Normal      Wet  Extreme-Wet

    ≤6375–6388         0.0         0.0     0.0         0.0      0.0          0.0

    6388–6391       1500.0      1500.0  1500.0      1500.0   1500.0       1500.0

      ≥6391         4000.0      4000.0  4000.0      4000.0   4000.0       4000.0
{'Dynamic': 1, 'Dyn_Type': 'year', 'Phase_Num': 2, 'Phase_Thresh': [10.0]}
```

After defining one or more transition and/or post-transition export criteria, the initial water level, emission scenario(s), and start and end year, a user can run the MLWB to produce water level, storage, and export values. After running the UCLA-MLM, the User Interface can output these results to an excel file that can be used to perform additional analysis and create additional figures in software such as Microsoft Excel. Additionally, several figures such as those outlined in **Section 4** and **Appendix D** can be produced within the User Interface based on the results from the simulation performed in the User Interface. The figures in the User Interface are interactive – for example: if 10 transition strategies were simulated, a user may choose to create a figure for a specific subset of those 10 transition strategies.

5.3   Robust Approaches for Selecting and Creating Export Criteria

UCLA's CCS is continuing to explore alternative export criteria, including data-driven data mining approaches for evaluating thousands of export conditions, such as those described in **Section 4.4**. **Appendix E** provides an early example of this effort; however, this data mining effort remains under development and is not intended to inform decision-making at this time. In parallel, algorithmic methods are being developed to generate new export options based on user-defined performance metrics. These efforts will likely include evaluation of additional transition and post-transition export criteria, with updates provided to the SWRCB as appropriate. Findings from this expanded assessment are expected to be documented in a separate academic journal publication and will be made available to the SWRCB as this effort matures.

6 CONCLUSION AND NEXT STEPS

This report documents the development of the UCLA-MLM, a water budget model designed to evaluate how Mono Lake water level responds to climate change under existing and alternative export criteria. To represent annual changes in Mono Lake storage, the UCLA-MLM simulates surface flows, evaporation, precipitation, and regulated exports throughout the Mono Basin. The UCLA-MLM was created in collaboration with the SWRCB, along with technical feedback from the MLTWG, including LADWP and MLC, and can reproduce observed Mono Lake levels with a mean absolute error of approximately 0.48 ft for the 1994 to 2020 period. Unlike models based on historical hydrology patterns alone, the UCLA-MLM incorporates regionalized (via downscaling), climate projections from Global Climate Models (GCMs) from California's 5th Climate Assessment (CA5), that were further refined to reflect observed conditions in the Mono Basin. This allows for the evaluation of long-term lake level under evolving climate conditions. Descriptions of future conditions in this report summary are based on the range of possible outcomes from the three emissions scenarios available from CA5 (SSP2-4.5, SSP3-7.0, and SSP5-8.5).

6.1   Climate Change Impacts on the Mono Basin and Mono Lake

Climate change has already altered the Mono Basin water budget – there is a high likelihood (>90% likelihood) that increased evaporation has already led to drier conditions relative to the pre-1990 period (**Figure 3-2**). Future projections indicate that increases in evaporation will continue but will be partially offset by increased precipitation. Relative to projections that do not account for climate change, climate change reduces the likelihood of Mono Lake being at or above 6,391 ft by approximately 15–42% 30 years from now and by 25–34% 60 years from now (**Table 4-3**). Lake level is predicted to have the best chance of being at or above 6,391 ft around 2064, but even without allowing any future exports, the likelihood peaks at only 42–73%, emphasizing the challenge of increasing the lake's water level under climate change.

6.2   Summary of Transition Export Criteria Evaluation

The transition export criteria apply until Mono Lake reaches 6,391 ft. Under the existing transition export criteria (**Table 4-1a**), the likelihood of reaching 6,391 ft within 30 years ranges from 18–46% (**Table 4-9**). This likelihood increases substantially if no exports are allowed, reaching 64–82%. While no exports offer the highest probability of reaching 6,391 ft within 30 years, several alternative transition export criteria that allow limited exports (e.g., A6 and A9 outlined in **Table 4-5**) yield comparable outcomes to no exports (**Table 4-9**).

6.3   Summary of Post-Transition Export Criteria Evaluation

The post-transition export criteria go into effect after 6,391 ft is met. Several post-transition export criteria were evaluated based on their ability to meet the D-1631 objective of sustaining a long-term average Mono Lake level of 6,392 ft, while still permitting some water exports. Their performance was also assessed using the percentage of time Mono Lake's water level remains above 6,390 ft, which is another metric documented in D-1631. The evaluation demonstrates that the existing post-transition export criteria is unlikely to meet the D-1631 goals (**Table 4-10**). Simulations with the existing criteria result in a post-transition water level that averages 6,389.3–6,390.5 ft and stays above 6,390 ft only 44–60% of the time. Modeling shows an alternative post-transition criteria (PT3) can improve lake outcomes, increasing the long-term average water level to 6,390.4–6,391.9 ft and increasing the percentage of time spent above 6,390 ft to 56–74%. Compared to the current post-transition export criteria, this alternative criteria (PT3) shifts the threshold for unlimited allowed exports from 6,391 ft to 6,393 ft and allows for limited exports between 6,391 ft and 6,393 ft during dry years (**Table 4-8**).

6.4 Summary of Transition and Post-Transition Export Criteria Evaluation

The combined effect of transition and post-transition export criteria—applied as they would be in practice under D-1631—was evaluated based on the likelihood of Mono Lake exceeding 6,391 ft, a level relevant to both the transition and post-transition objectives outlined in D-1631. To explore a range of management strategies in between No Exports and Existing Exports, an array of transition export criteria were assessed when coupled with the PT3 post-transition export criteria. When combined with a no export transition criteria, the likelihood of being at or above a 6,391 ft water level under PT3 over the next 30 years (through 2054) is only reduced by roughly 10% compared to No Exports at all. When alternative transition criteria are combined with PT3, several of them (e.g., A6, A9) result in only minor additional reductions— less than 5%—in the likelihood of a water level above 6,391 ft relative to no exports in the transition period combined with PT3 in the post-transition period (**Table 4-11**). Generally, the dynamic criteria assessed here (e.g., A7, U1-U4) allow for higher initial exports but result in slightly reduced chances of being at or above a 6,391 ft water level, however, dynamic export criteria could be further explored with the UCLA-MLM User Interface. By 60 years from now (2084), differences among the transition export criteria become less pronounced since variations in the likelihood of being at or above 6,391 ft becomes more strongly influenced by a larger number of GCMs in the post-transition period (**Table 4-11**).

6.5   UCLA-MLM Limitations and Uncertainties

UCLA-MLM underwent rigorous evaluation, and while it was found to provide reliable representation of observed conditions, some uncertainties remain. While all GCMs predict increases in evaporation, climate projections, particularly for precipitation and runoff, can vary widely (**Figure 3-2**). This variability is also apparent in the large geographic variations in projected precipitation changes (**Figure 3-5**), which could contribute to opposing trends in different precipitation driven components like Sierra Nevada runoff and ungauged runoff. These differences, while not uncommon in regional climate projections, contribute to variability in lake level projections (**Figure 4-4**) and emphasize the importance of treating each GCM as a plausible future in a probabilistic or likelihood framework (e.g. **Figure 4-5**). Despite these uncertainties, GCMs generally agree that Mono Lake water level has already decreased due to the historic climate change that occurred between the 1950s and present-day (e.g. **Figure C-10, C-23**). Lastly, it's important to note that climate change signals can take up to two decades to noticeably influence Mono Lake storage (and thus water level) relative to conditions without climate change. This is largely due to internal variability. To account for this, caution should be exercised when using the UCLA-MLM to assess the influence of climate change using time frames shorter than 20 years.

The MLWB applies a process-based approach to represent all major components of the hydrologic cycle across the Mono Basin. It uses spatially distributed weather data, including precipitation, evaporation, and runoff, derived from the ERA5-WRF dataset. Because the ERA5-WRF dataset contains biases, corrections were applied using available observational data. In cases where observations were unavailable, such as evaporation from Mono Lake, adjustments were made based on the overall water balance and its ability to reproduce historic observations of lake level. In addition, the MLWB utilizes a statistical relationship to estimate regulated flow into Mono Lake based on natural flow from the hydrologic model. The relationship was derived from observed regulated flow data from 1994 to 2019. This method performs well over a broader observational period (1971 to 2019), indicating limited sensitivity to changes in land use. However, significant changes in future flow regulation could require updates to these regression relationships. Altogether, the MLWB simulates observed lake levels with a mean absolute error of approximately 0.48 ft for the 1994 to 2020 period. Sensitivity analyses in **Appendix A.4** show that while different modeling assumptions can shift ensemble mean projections by about 0.5 ft, the likelihood of Mono Lake being above a given water level, a more robust metric, remains largely unchanged.

Lastly, the MLWB operates at an annual time step, capturing long-term trends in Mono Lake's water budget under climate and export scenarios. It is not designed to represent daily or monthly operations and is not intended for short-term operational planning. Although it accounts for annual instream flow constraints on exports, the UCLA-MLM is ultimately designed to support long-range water management and export analysis under varying climate conditions.

6.6   Future Work and Final Thoughts

The UCLA-MLM User Interface will be available by request to support further analysis of export criteria. Additional export criteria not covered in this report may be explored using this User Interface. Ongoing analysis using UCLA-MLM should also be supplemented with other models of Mono Lake behavior, including the Vorster model and *e*STREAM. However, caution is advised when relying solely on observed or historical data, as these approaches may underestimate the impacts of climate change and thus overstate the likelihood for lake recovery.

Overall, these findings underscore the importance of explicitly incorporating climate change into Mono Lake management. Even under no exports, a water level above 6,391 ft remains uncertain, especially under changing climate conditions which are predicted to significantly reduce the likelihood for being at or above 6,391 ft (e.g. **Table 4-3**). A limited set of export criteria (e.g. A6, A9) do allow for some LADWP exports while maintaining greater than a 60% likelihood of reaching 6,391 ft within 30 years (e.g. **Table 4-9**). However, these export criteria are still associated with delays and diminished chances of reaching 6,391 ft, which may be of concern. Strategic, adaptive management will be essential to protect Mono Lake as a vital public resource in the decades ahead.

References

Almazroui, M. I (2021). Projected Changes in Temperature and Precipitation Over the United States, Central America, and the Caribbean in CMIP6 GCMs. *Earth Syst Environ*, 5, 1–24 https://doi.org/10.1007/s41748-021-00199-5.

Bass, B., Su, L., and Lettenmaier, D. (2023, November). *California Energy Commission, Climate Data and Analysis Working Group (C-DAWG).* Retrieved from Data Adoption Justification Memo (for California's Fifth Climate Change Assessment): Hydrology Projections: https://analytics.cal-adapt.org/data/more_data/.

Bass, B. et al. (2022). Natural Variability Has Concealed Increases in Western US Flood Hazard Since the 1970s. *Geophysical Research Letters*.

California Energy Commission (accessed 7/15/2025). Climate Data and Analysis Working Group (C-DAWG): California Climate Change Assessment Data Summaries. https://www.energy.ca.gov/programs-and-topics/topics/research-and-development/climate-data-and-analysis-working-group-c-dawg.

California State Water Resources Control Board (1994). *Mono Lake Basin Water Right Decision 1631.*

California State Water Resources Control Board (2021). *Right to Divert and Use Water, Amended License 10191.*

Coles, S. (2001). An Introduction to Statistical Modeling of Extreme Values. *Springer-Verlag, https://doi.org/10.1007/978-1-4471-3675-0.*

Eyring et al., V. S. (2016). Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) Experimental Design and Organization. *Geoscientific Model Development*, 1937-1958, https://doi.org/10.5194/gmd-9-1937-2016.

Gochis et al., M. B. (2020). *The WRF-Hydro® modeling system technical description, (Version 5.1.1).* . Available online at: https://ral.ucar.edu/sites/default/files/public/WRFHydroV511TechnicalDescription.pdf.

Harding et al., B. W. (2012). The implications of climate change scenario selection for future streamflow projection in the Upper Colorado River Basin. *Hydrology and Earth System Sciences*, 3989-4007, https://hess.copernicus.org/articles/16/3989/2012/hess-16-3989-2012.pdf.

Hawkins, E. a. (2009). The Potential to Narrow Uncertainty in Regional Climate Predictions. *Bulletin of the American Meteorological Society,* 1095-1108, https://doi.org/10.1175/2009BAMS2607.1.

Held, I. a. (2006). Robust Responses of the Hydrological Cycle to Global Warming. *Journal of Climate,* 5686-5699.

Hersbach, H. B. (2020). The ERA5 global reanalysis. *Quarterly Journal of the Royal Meteorological Society,* 146 (730), 1999-2049.

Huard, D. F.-P.-I. (2022). Estimating the Likelihood of GHG Concentration Scenarios From Probabilistic Integrated Assessment Model Simulations. *Earth's Future.*

Intergovernmental Panel on Climate Change (IPCC) (2014). *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.*

IPCC. (2023). *Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.*

Kling et al., H. M. (2012). Runoff conditions in the upper Danube basin under an ensemble of climate change scenarios. *Journal of Hydrology.*

Knutti, R. F. (2010). Challenges in combining projections from multiple climate models. *Journal of Climate,* 23(10), 2739-2758.

Krantz et al., W. P. (2021, November 29). Retrieved 1 November, 2023, from https://www.energy.ca.gov/sites/default/files/2022-09/20220907_CDAWG_MemoEvaluating_GCMs_EPC-20-006_Nov2021-ADA.pdf

LADWP. (2020). *Urban Water Management Plan.* Retrieved 1 November, 2023, from https://www.ladwp.com/sites/default/files/documents/LADWP_2020_UWMP_Web.pdf.

Lehner, F., Deser, C., Simpson, I. R., & Terray, L. (2018). Attributing the U.S. Southwest's recent shift into drier conditions. Geophysical Research Letters, 45, 6251–6261. https://doi.org/10.1029/2018GL078312.

Los Angeles Department of Water and Power. (2022). *Mono Basin Operations Plan.*

Mastrandrea, M. D.-K. (2011). The IPCC AR5 guidance note on consistent treatment of uncertainties: a common approach across the working groups. *Climatic Change,* 108(4), 675–691.

McBain & Trush, Inc. and Ross Taylor and Associates. (2010). *Mono Basin Stream Restoration and Monitoring Program: Synthesis of Instream Flow Recommendations to the State Water Resources Control Board and the Los Angeles Department of Water and Power*.

Mono Lake Committee. (2022, 3 29). *Groundwater exports benefit Los Angeles, impact Mono Lake*. Retrieved 11 27, 2024, from https://www.monolake.org/today/groundwater-exports-benefit-los-angeles-impact-mono-lake.

Mono Lake Committee, V. C. (2024). *A Water Balance Forecast Model for Mono Lake (The Vorster Model)*.

Mono Lake Technical Group. (2024). *Presentation on 5/2/2024*.

National Center for Atmospheric Research. (2022). *Noah-Multiparameterization Land Surface Model (Noah-MP LSM)*. Retrieved 1 1, 2022, from https://ral.ucar.edu/solutions/products/noah-multiparameterization-land-surface-model-noah-mp-lsm.

Penman, H. (1948). Natural evaporation from open water, bare soil and grass. *Proceedings of the Royal Society of London*, 193 (1032), 120–145.

Pierce, D. C. (2015). Improved Bias Correction Techniques for Hydrological Simulations of Climate Change. *Journal of Hydrometeorology*, 2421-2442.

Pierce et al., D. S. (2023, December). *California Energy Commission, Climate Data and Analysis Working Group (C-DAWG)*. Retrieved from Data Adoption Justification Memo (for California's Fifth Climate Change Assessment) LOCA Version 2 - Training Data. https://www.energy.ca.gov/sites/default/files/2024-03/03_LOCA2-forCA-TrainingData_DataJustificationMemo_Pierce_Adopted_ada.pdf

Pierce et al., D. S. (2023b, December). *California Energy Commission, Climate Data and Analysis Working Group (C-DAWG)*. Retrieved from Data Adoption Justification Memo (for California's Fifth Climate Change Assessment) LOCA Version 2 Hybrid Downscaling. https://www.energy.ca.gov/sites/default/files/2024-03/04_HybridDownscaling_DataJustificationMemo_Pierce_Adopted_ada.pdf.

Rahimi et al., S. K.-H. (2022). Evaluation of a reanalysis-driven configuration of WRF4 over the western United States from 1980 to 2020. *Journal of Geophysical Research: Atmospheres*, 127, e2021JD035699.

Raumann, C.G., Stine, S., Evans, A., Wilson, J., 2002, Digital Bathymetric Model of Mono Lake, California (Version 1.0): U.S. Geological Survey Miscellaneous Field Studies Map 2393. https://doi.org/10.3133/mf2393.

Shiogama, H. et al. (2023). Important distinctiveness of SSP3–7.0 for use in impact assessments. *Nature Climate Change Comment*, 1276-1278.

State Water Resources Control Board. (1994). *Mono Lake Basin Water Right Decision 1631*.

USGS. (2021). *USGS EROS archive - Land Cover Products - Global Land Cover Characterization (GLCC)*. Retrieved 1 1, 2021, from https://doi.org/10.5066/F7GB230D

Vorster, P. (1985). *Master's Thesis: A Water Balance Forecast Model for Mono Lake, California*. Hayward State University, California.

Watercourse Engineering. (2020). *Mono Lake Elevation Studies, Technical Memorandum, Appendix E*.

Weins, J. P. (1993). Assessing ecological impact assessment: Lessons from Mono Lake, California. *Ecological Applications*, 3 (4), 595-609.

Williams, A. C. (2022). Rapid intensification of the emerging southwestern North American megadrought in 2020–2021. *Nature Climate Change*, 12, 232-234.