Lower Colorado River Mainstream Evaporation and Riparian Evapotranspiration Losses Report

Interior Region 8: Lower Colorado Basin

U.S. Department of the Interior

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Mission Statements

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

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

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Cover Photo: Sunrise at the Laguna Division Conservation Area, downstream of Imperial Dam.

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Acronyms and Abbreviated Terms

AF	Acre-feet
ASCE	American Society of Civil Engineers
AZMET	Arizona Meteorological Network
CIMIS	California Irrigation Management Information System
CRMMS	Colorado River Mid-Term Modeling System
CRSS	Colorado River Simulation System
ESP	Ensemble Streamflow Prediction
ET	Evapotranspiration
ft	Feet
GIS	Geographic Information Systems
HDB	Hydrologic Database
kAF	Thousand acre-feet
LCRAS	Lower Colorado River Annual Summary
NAIP	National Agricultural Imagery Program
NIB	Northerly International Boundary
NWS	National Weather Service
Reclamation	United States Bureau of Reclamation
SIB	Southerly International Boundary
US	United States
USGS	United States Geological Survey

Glossary

AZMET: A network of automated weather stations within the state of Arizona that provide reference evapotranspiration estimates.

CIMIS: A network of automated weather stations within the state of California that provide reference evapotranspiration estimates.

Evaporation: The process of converting liquid water to a vapor

Evapotranspiration: The combined effect of evaporation from the soil surface and transpiration from the plant canopy.

Geographic Information System: An information system that integrates, stores, edits, analyzes, shares, and displays geographic information.

National Weather Service: An agency of the United States federal government that is tasked with providing observed climate data, weather forecasts, warnings of hazardous weather, and other weather-related products to organizations and the public for the purposes of protection, safety, and general information.

Reference Evapotranspiration: The evapotranspiration rate from a reference surface. The reference surface is a hypothetical reference crop with specific characteristics.

Riparian Vegetation: Riparian vegetation refers to the vegetation that grows along the shores of freshwater rivers and lakes, or along some canals. As used in this report, riparian vegetation classes also include wetland types and natural vegetation within the lower Colorado River floodplain.

Seepage: The slow movement or percolation of water through soil or rock. Movement of water through soil without formation of definite channels. The movement of water into, through, and out of the soil from unlined canals, ditches, and water storage facilities.

Spectral Characteristics: The amount of spectral reflectance from the Earth's surface recorded by the satellite sensors in different portions of the electromagnetic spectrum for different land cover types.

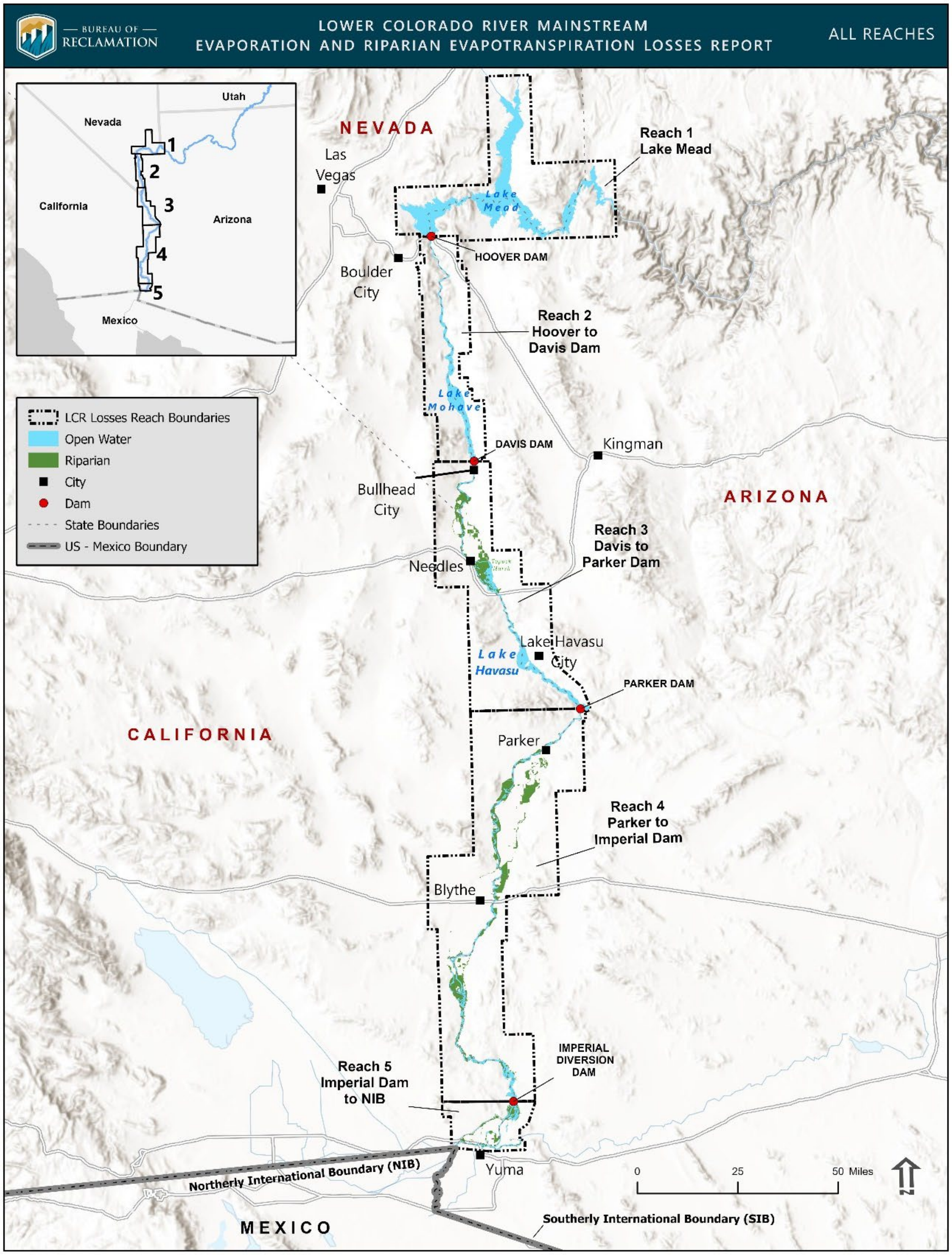

Figure 1. Map of reaches identified in the Lower Colorado River Mainstream Evaporation and Riparian Evapotranspiration Losses Report

Executive Summary

On August 16, 2022, the Bureau of Reclamation (Reclamation) and Department of the Interior announced several administrative actions for consideration to improve and protect the long-term sustainability of the Colorado River System. The System is currently experiencing prolonged drought and low runoff conditions accelerated by climate change that have led to historically low water levels in Lakes Powell and Mead (Reclamation, 2021). One of the actions included reviewing and prioritizing additional administrative initiatives to address system losses in the lower Colorado River mainstream. As part of that action, this report provides an overview of historical mainstream evaporation and riparian evapotranspiration (ET) losses along the lower Colorado River and presents methodologies used to develop those datasets. This report does not make recommendations on how to account for system losses in the lower Colorado River mainstream.

Data provided in this report were divided into five reaches, listed below. Data sources used for each reach are described in Chapter 2.

- Reach 1: Lake Mead
- Reach 2: Hoover Dam to Davis Dam
- Reach 3: Davis Dam to Parker Dam
- Reach 4: Parker Dam to Imperial Dam
- Reach 5: Imperial Dam to the Northerly International Boundary (NIB) with Mexico

This report presents two datasets: (1) Lower Colorado River Annual Summary (LCRAS) of ET and Evaporation; and (2) Reclamation's hydrologic database (HDB). The LCRAS dataset uses aerial imagery to determine open water and riparian acreages, then applies area and cover type ET coefficients to calculate evaporation and riparian ET estimates along the mainstream lower Colorado River and reservoirs between Hoover Dam and Mexico. HDB contains a computational processor that estimates evaporation losses from the lower Colorado River mainstream reservoirs (Lake Mead, Lake Mohave and Lake Havasu) based on lake elevations, the related surface water area, and monthly evaporation coefficients specific to each reservoir. HDB stores these estimates in its database. It does not provide evaporation estimates from the river sections between reservoirs and does not provide estimates of riparian ET. Methodologies to develop these datasets are described in more detail in Chapter 3.

Chapter 4 separately summarizes evaporation loss estimates available from LCRAS and HDB, then compares these two datasets at Lake Mohave and Lake Havasu, since both datasets can be used to estimate evaporation at these reservoirs. From 2017 to 2021, the average annual evaporation loss for Reach 1 through Reach 5 is estimated to be about 860 thousand acre-feet (kAF). This estimate uses HDB evaporation data for Reach 1, since LCRAS data is not available for that reach, then uses LCRAS data for Reaches 2 through Reach 5 to maintain as much consistency in the data sources as possible.

Chapter 5 summarizes riparian ET estimates available using LCRAS. Riparian ET estimates are not available for Reach 1: Lake Mead but is available for Reach 2 through Reach 5. From 2017 to 2021, the average annual riparian ET loss for Reach 2 through Reach 5 is estimated to be about 445 kAF.

Chapter 6 summarizes the total system losses, which is the combined evaporation and riparian ET data for each reach. From 2017 to 2021, the average annual total system loss (evaporation and riparian ET) for Reach 1 through Reach 5 is estimated to be about 1,304 kAF. Chapter 7 provides a summary of the data from the report.

1 Introduction

The Colorado River System provides essential water supplies to approximately 40 million people, nearly 5.5 million acres of agricultural lands, hydroelectric renewable power, recreational opportunities, habitat for ecological resources, and other benefits across the southwestern United States and northwestern Mexico (Reclamation, 2012). While the annual flow of the Colorado River and its tributaries varies considerably from year to year, the Colorado River System is currently experiencing prolonged drought and low runoff conditions accelerated by climate change that have led to historically low water levels in Lakes Powell and Mead (Reclamation, 2021). The period from 2000 through 2022 is the driest 23-year period in more than a century[1] and one of the driest periods in the last 1,200 years (Meko et al., 2007).

On August 16, 2022, the Bureau of Reclamation (Reclamation) and Department of the Interior announced several administrative actions for consideration to improve and protect the long-term sustainability of the Colorado River System (Reclamation, 2022a). These actions were identified in the context of the low reservoir conditions as described in Reclamation's Colorado River Basin August 2022 24-Month Study[2].

The administrative actions in the Lower Basin included reviewing and prioritizing additional administrative initiatives that would ensure maximum efficient and beneficial use of urban and agricultural water, and address evaporation, seepage, and other system losses in the Lower Basin. As part of that action, this report provides an overview of evaporation and riparian evapotranspiration (ET) losses along the lower Colorado River mainstream. The report presents methodologies that have been used to develop those datasets; however, it does not make recommendations on how to implement or account for system losses from the lower Colorado River mainstream. Data regarding seepage to groundwater were not included in this report. Seepage along the mainstream of the lower Colorado River is not considered to be a loss from the system as water entering the aquifer will re-emerge further downstream within the Colorado River.

Estimates of lower Colorado River mainstream evaporation and riparian ET losses provided in this report were divided into five reaches, as follows:

- Reach 1: Lake Mead
- Reach 2: Hoover Dam to Davis Dam
- Reach 3: Davis Dam to Parker Dam
- Reach 4: Parker Dam to Imperial Dam
- Reach 5: Imperial Dam to the Northerly International Boundary (NIB) with Mexico

[1] The Colorado River Basin natural flow record is available at https://www.usbr.gov/lc/region/g4000/NaturalFlow/provisional.html.
[2] For more information on the 24-Month Study Projections, see https://www.usbr.gov/lc/region/g4000/riverops/24ms-projections.html.

A map of the reaches is provided in Figure 1, on page ix. More detail on each individual reach is provided in maps included in Appendix 1.

2 Data Sources

This report summarizes data from two datasets: (1) Lower Colorado River Annual Summary (LCRAS) of ET and Evaporation[3]; and (2) Reclamation's hydrologic database (HDB)[4]. These two datasets were developed using separate methodologies for calculating evaporation and riparian ET losses, as described below:

1) The LCRAS dataset is derived from Reclamation's LCRAS reports, which provide estimates of annual agricultural, riparian vegetation, and open-water evaporation and evapotranspiration along the lower Colorado River from Hoover Dam to the Southerly International Boundary (SIB) with Mexico. The method used to create this dataset involves estimation of water use for a specific land cover type (open water, riparian vegetation type, or crop) using acreages derived yearly from Geographic Information Systems (GIS), a daily standardized ASCE Penman-Monteith reference ET rate for short crops, and a daily cover-type-specific coefficient.

2) HDB calculates and stores evaporation data from the lower Colorado River mainstream reservoirs (including Lake Mead, Lake Mohave, and Lake Havasu) based on lake elevations and related surface-water area, along with monthly evaporation coefficients that have been previously determined for each reservoir. The computational processor in HDB derives an average water surface area for the reservoir based on the area-capacity tables[5], then multiplies that surface area by the monthly evaporation coefficients specific to the reservoir. These calculations are completed on a daily timestep, and daily values are summed to get monthly and annual data. This method does not calculate evaporation or riparian ET losses along the Colorado mainstream.

Reclamation's operations and planning models, such as the Colorado River Mid-term Modeling System (CRMMS) and the Colorado River Simulation System (CRSS), cannot be used to calculate historical evaporative and riparian losses. Instead, these models are used to calculate possible future evaporation losses based on possible future reservoir conditions. To do this, these models use the same method that HDB uses to calculate historical evaporation, except that the evaporation projections in the models use a monthly timestep instead of a daily timestep[6]. Reclamation does model estimates of historical intervening flows or losses from Lees Ferry to the Northerly International Boundary (NIB) with Mexico using the Lower Colorado Gain/Loss Model, but they are calculated as the residual of a water balance equation and do not provide a

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[3] For more information on LCRAS, see https://www.usbr.gov/lc/region/g4000/wtraccttypes.html#LCRAS.
[4] HDB is the foundation for Reclamation's Database of Record. More information on HDB is available at: http://www.hydrodb.net/#:~:text=The%20Hydrologic%20Database%20(HDB)%20is,various%20systems%20and%20personal%20spreadsheets.
[5] Lake Mead's elevation and the area and capacity tables are available at https://www.usbr.gov/lc/region/g4000/LM_AreaCapacityTables2009.pdf.
[6] While HDB calculates evaporation on a daily timestep, then sums the daily estimates to obtain monthly and annual values, the models only calculate evaporation on a monthly timestep, therefore evaporation estimates in the models will slightly differ from HDB.

breakdown of the mainstream evaporative or riparian ET losses, and are also computed on a monthly timestep instead of a daily timestep.

Reach 1, which only includes Lake Mead, calculates evaporation losses from HDB using evaporation coefficients specific to the lake[7]. There are no LCRAS data for this reach.

Mainstream evaporation and riparian evapotranspiration estimates for Reaches 2 through 5 are from the LCRAS dataset. The LCRAS open water data accounts for the mainstream lower Colorado River, reservoirs, lakes, lagoons, and other backwater area surfaces. These estimates utilize the acreage of water derived from GIS combined with three sets of evaporation coefficients that are specific for reaches two and three, four, and five. Mainstream evaporation losses from the lower Colorado River reservoirs were included in the reach datasets (for example, Lake Mohave evaporation was included in Reach 2). The LCRAS riparian data accounts for all the riparian habitat within floodplain of the lower Colorado River to the SIB. Riparian losses for Reaches 2 through 5 also use a GIS layer to determine the acreage of six different riparian vegetation classes. Each vegetation class has its own specific coefficients that are used in all reaches.

In addition to being used to estimate evaporation losses for Reaches 2 through 5, the LCRAS open water GIS dataset was used to estimate evaporation from Lake Mohave and Lake Havasu separately, to provide comparison to the evaporation estimates from HDB.

HDB includes estimates of evaporation losses from Lake Mead, Lake Mohave, and Lake Havasu. The original evaporation coefficients used to estimate evaporative losses were based on Class-A Pan evaporation studies. Those coefficients are still used to estimate evaporation at Lake Havasu. Evaporation coefficients for Lake Mead and Lake Mohave were updated in 2021 after a multi-year evaporation study was performed by the United States Geological Survey's (USGS) Nevada Water Science Center in Boulder City, Nevada (USGS, 2017). Reclamation's Boulder Canyon Operations Office completed a sensitivity analysis, following Reclamation's formal Peer Review process, on the new evaporation coefficients before updating the coefficients for modeling and reporting purposes[8] (Reclamation, 2022b). The new evaporation coefficients were applied to the entire Lake Mead 2001 – 2021 dataset and the Lake Mohave 2017 – 2021 dataset for this report since they provide a more accurate temporal distribution and evaporation magnitude at Lake Mead and Lake Mohave. These evaporation coefficients may be revisited and adjusted in the future to incorporate the most recent reservoir elevation and regional climate trends.

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[7] Evaporation losses between Lees Ferry and Lake Mead, and riparian ET losses between Lees Ferry and Hoover Dam, are not included since those data are not available in current Reclamation datasets. While Reclamation's operations and planning models provide a gains/losses term between Lee's Ferry and Lake Mead, it is calculated as the residual of a water balance equation and does not provide a breakdown of the evaporative or riparian ET losses.
[8] The new USGS coefficients are used in the official HDB record starting in October 2021. Reclamation's operations and planning models were updated after Reclamation completed the sensitivity analysis (Reclamation, 2022b). The USGS coefficients were implemented in the Colorado River Mid-Term Modeling System (CRMMS) in April 2022, and in the Colorado River Simulation System (CRSS) in version 6, released in April 2023. More information on these models is available at: https://www.usbr.gov/lc/region/g4000/riverops/model-info.html#policy.

Table 1 summarizes the evaporation and riparian ET data sources used for each reach. Additional details on the methodology used to estimate evaporation and riparian ET loss estimates are provided in Chapter 3 of this report. Evaporation losses are summarized in Chapter 4 and provided in Appendix 2 (LCRAS Data) and Appendix 3 (HDB Data). Riparian ET losses are summarized in Chapter 5 and provided in Appendix 4.

Table 1. Data source for mainstream evaporation and riparian ET losses.

Reach	Evaporation Data Source	Riparian ET Data Source
Reach 1: Lake Mead	HDB	N/A
Reach 2: Hoover Dam to Davis Dam	HDB (Lake Mohave only) & LCRAS Open Water	LCRAS Riparian
Reach 3: Davis Dam to Parker Dam	HDB (Lake Havasu only) & LCRAS Open Water	LCRAS Riparian
Reach 4: Parker Dam to Imperial Dam	LCRAS Open Water	LCRAS Riparian
Reach 5: Imperial Dam to NIB	LCRAS Open Water	LCRAS Riparian

3 Methodology

This section describes the methodologies used to develop the loss datasets in LCRAS and HDB, which were compiled for this report.

The LCRAS loss estimates were compiled in this study to estimate evaporation and riparian ET losses along the mainstream lower Colorado River and reservoirs between Hoover Dam and the NIB. While LCRAS data are available to the SIB, the NIB is the location at which water is officially delivered to Mexico and no longer under US jurisdiction. As a result, this report only presents data to the NIB. The methodology to develop the LCRAS dataset is described in Section 3.1. HDB was used to estimate evaporation from Lake Mead, Lake Mohave, and Lake Havasu based on lake elevations. The methodology for that dataset is described in Section 3.2.

Evaporation estimates using the LCRAS data were compiled for Lake Mohave and Lake Havasu separately to compare those evaporation estimates to the data from HDB.

3.1 Data from LCRAS

Reclamation routinely estimates mainstream evaporation and riparian ET losses for Reaches 2 through 5. The estimates are calculated using a combination of weather data and GIS databases containing the spatial boundaries of open water and riparian cover along the mainstream of the lower Colorado River below Hoover Dam.

Key components of the calculations include:

1) Identifying open-water and riparian areas and tabulating acreages associated with each land cover type (riparian vegetation group or open water) on a yearly basis.
2) Determining the average daily reference ET for each reach.
3) Applying the daily evaporation and ET coefficients for each land cover type (riparian vegetation group or open water) to derive a daily, monthly, or yearly ET rate for each land cover type.

These components are described in more detail in the following sections.

3.1.1 LCRAS Open Water GIS Layer

The initial LCRAS open-water spatial dataset was digitized based on aerial imagery at the beginning of the LCRAS program in 1995 (Reclamation, 1997). Water body types included in this report from the open water dataset are described in Table 2.

Table 2. Water body types from the open water dataset included in this report.

Water Type	Description
Main Channel	The main channel of the lower Colorado River, including all mainstream reservoirs.
Backwater	A water body that is hydrologically connected to, but not part of, the main channel of the Colorado River.
Marina	Main channel reaches or backwaters that are being used as marinas.

3.1.1.1 Yearly Updates of the Open Water GIS Layer

Each year, the open water GIS layer is updated by comparing it to the most recent aerial and satellite imagery available. Imagery and datasets from previous years may be consulted to ensure that the changes seen in a particular year are not the result of yearly fluctuation of water levels or differences due to the timing of image acquisition.

3.1.2 LCRAS Riparian GIS Layer

The current LCRAS riparian layer was created beginning with the 2010 calendar year (Reclamation, 2014). During this effort, the riparian areas along the mainstream were classified into 6 different vegetation types using 1-meter resolution National Agricultural Imagery Program (NAIP) imagery and object-based image analysis with eCognition® Developer software (Trimble, Inc.).

Riparian vegetation classes are shown in Table 3.

Table 3. Riparian vegetation types in the LCRAS GIS Layer.

Riparian Vegetation Type	Description
Barren	Less than 10% vegetation
Cottonwood/Willow	61% to 100% cottonwood and willow
Marsh	40% cattail, bulrush, and phragmites
Mixed Veg Low	Mixed vegetation types that may include salt cedar, mesquite, or arrowweed with crown closure greater than or equal to 10% and less than 40%
Mixed Veg Medium	Mixed vegetation types that may include salt cedar, mesquite, or arrowweed with crown closure greater than or equal to 40% and less than or equal to 80%
Salt Cedar Dense	Predominant salt cedar with crown closure greater than 80%

3.1.2.1 Yearly updates of the Riparian GIS layer

Since 2010, the riparian GIS layer has been updated each year by comparing the current year's satellite imagery (Landsat or Sentinel) to the previous year's imagery and determining where changes have occurred.

The change detection procedure is as follows:

1) Create a principal components image from a mosaiced image of the entire area of interest (the mainstream of the river from Hoover Dam to NIB) in the current year. Principal components compress data from a multiband raster into one band to be used for comparison.

2) Compare the new principal component image and other imagery to the previous year's imagery to visualize where change has occurred. It is important that the two images being compared are as close as possible to exactly one year apart.

3) Review areas where change has occurred and edit the riparian layer to reflect those changes in the current year. Due to the relatively coarse resolution of the satellite imagery, only changes greater than a few acres are detected, such as new development, land clearing or burned areas.

4) Additional updates are made when higher resolution imagery is available (e.g. NAIP).

3.1.3 Calculating Reference ET

Reference ET represents a standardized measure of the rate of water use by vegetation (in linear units, such as inches) to which the rate of water use of all types of vegetation (as well as the rate of evaporation from a body of water) can be related.

Reclamation uses reference ET values calculated with the standardized Penman-Monteith equation developed by the American Society of Civil Engineers (standardized equation) for short crops (ASCE 2005), and climatological data provided by the Arizona Meteorological Network (AZMET) and California Irrigation Management Information System (CIMIS) automated weather stations. These stations are located in irrigated areas along the Colorado River from Davis Dam to Mexico. The AZMET and CIMIS stations continuously collect maximum, minimum, and average air temperature and relative humidity; average soil temperature, wind speed, and precipitation data; and calculate net solar radiation. Reclamation downloads these parameters from the AZMET and CIMIS websites[9] and uses them to calculate hourly and daily reference ET rates. Reclamation maintains a contract with the University of Arizona, which is the operator of the AZMET network, to provide data quality review for those AZMET and CIMIS stations used in the LCRAS program.

Table 4 provides a list of the stations used to collect the reference ET data used in Reclamation's calculations and the corresponding geographical areas and reaches for which each station's data are applied.

[9] The AZMET website can be found here: https://cals.arizona.edu/azmet/. The CIMIS website can be found here: https://cimis.water.ca.gov/.

Table 4. LCRAS areas and associated weather stations for the calculation of reference ET along each reach.

Area	Reach	Weather Stations	
		AZMET	CIMIS
Mohave Valley area	Reach 2: Hoover Dam to Davis Dam Reach 3: Davis Dam to Parker Dam	Mohave Mohave II Mohave ETo	--
Parker/Palo Verde valleys	Reach 4: Parker Dam to Imperial Dam	Parker Parker II	Blythe NE Ripley Palo Verde II
Yuma area	Reach 5: Imperial Dam to the NIB	Yuma North Gila Yuma South Yuma Valley Yuma Valley ETo	--

3.1.4 ET Coefficients for Open Water and Riparian Types

ET coefficients (abbreviated Kc) are the values that relate reference ET rates to the ET rate of a specific riparian vegetation group, as well as to the open-water evaporation rate from a body of water. Multiplying the reference ET by the ET coefficient for a type of riparian vegetation or body of water results in an estimate of the amount of water consumed by that land cover type for a particular day. *Coefficients for Vegetative Evapotranspiration and Open Water Evaporation for the Lower Colorado River Accounting System*, Jensen, Marvin E. (1998*),* presents the rationale used to develop the original riparian vegetation groups along the lower Colorado River and the Bill Williams River, their respective ET coefficients, and open water evaporation coefficients. *Vegetative and Open Water Coefficients for the Lower Colorado River Accounting System (LCRAS), Addendum to the 1998 Report*, Jensen, Marvin E. (2003), presents the adjustments made to the crop and riparian vegetation groups and the ET and evaporation coefficients. In general, open water coefficients were developed using an energy balance - aerodynamic approach (Jensen 1998, 2003). Development of riparian vegetation coefficients for cottonwood/willow and marsh cover types also used a similar approach along with the linear segment crop coefficient curve (FAO-24, 1977, Jensen 1998, 2003) to account for plant phenology.

ET Coefficients for salt cedar dense, mixed vegetation medium, mixed vegetation low, and barren vegetation types were based on USGS (2006), *Evaporation by Phreatophytes Along the Lower Colorado River at Havasu National Wildlife Refuge, Arizona*. In this study, ET was directly measured using Bowen ratio stations to generate updated daily ET coefficients for these four riparian vegetation types. Study areas for cottonwood/willow and marsh were not updated in this study, therefore, coefficients for these vegetation types were maintained from Jensen (2003).

Evaporation calculations for open-water surfaces along the mainstream of the lower Colorado River use unique evaporation coefficients for each geographical area (Jensen, 2003), as described in Table 5. The coefficients are included in Appendix 5. The final ET rates based on the reference ET and daily coefficients are presented in Appendix 6.

Table 5. Source for evaporation and evapotranspiration daily coefficients.

Land Cover Type	Applicable Reaches	Source
Open Water	Hoover Dam to Parker Dam	Jensen (2003) Page 69, Column 2
Open Water	Parker Dam to Imperial Dam	Jensen (2003) Page 69, Column 3
Open Water	Imperial Dam to NIB	Jensen (2003) Page 69, Column 4
Barren	All Reaches	USGS (2006) (Barren)
Cottonwood/Willow	All Reaches	Jensen (2003)
Marsh	All Reaches	Jensen (2003)
Mixed Veg Low	All Reaches	USGS (2006) (Arrowweed)
Mixed Veg Medium	All Reaches	USGS (2006) (Mixed Vegetation)
Salt Cedar Dense	All Reaches	USGS (2006) (Salt Cedar Dense)

3.1.5 Calculating LCRAS Open Water Evaporation

Reclamation calculates estimates of evaporation from Lake Mohave and Lake Havasu, and the open water areas of the mainstream Colorado River channel and its adjacent backwaters (such as Topock Marsh and Mittry Lake) from below Hoover Dam to the NIB. For the purposes of this report, to be consistent with calculations in Reach 1, the method used in this report departs from the normal LCRAS method in that it does not subtract precipitation from estimates of evaporation. Therefore, the following equation is used to calculate evaporation from open water areas:

$$\text{Annual EVAP} = \sum_{t=0}^{n} \frac{[(ET_o \times K_c)]\ AC}{12 \text{ inches/foot}}$$

Where:

EVAP = Annual Evaporation by open water (acre-feet [AF])

n = Time-step (monthly)

ET_o = Daily reference ET (inches)

K_c = Monthly Evaporation coefficient for water (dimensionless)

AC = Acres of water

Evaporation is summed by reach for the LCRAS open water data.

3.1.6 Calculating Riparian ET

To calculate ET from riparian vegetation, Reclamation calculates an ET rate for each vegetation type by multiplying the average daily reference ET values by each type's unique daily ET coefficient (dimensionless). Reclamation sums the daily ET rates to produce a monthly ET rate for each vegetation type. Reclamation calculates the ET within each reach by multiplying the ET rate for each vegetation type by its acreage. These calculations are performed on a monthly time-step and the results summed to produce annual riparian ET values. The following equation is used to calculate ET for a specific vegetation type:

$$\text{Annual ET} = \sum_{t=0}^{n} \frac{[(ET_o \times K_c)]\ AC}{12\ \text{inches/foot}}$$

Where:

ET	=	Annual ET by vegetation type (AF)
n	=	Time-step (monthly)
ET_o	=	Daily reference ET (inches)
K_c	=	Daily ET coefficient for a specific vegetation type (dimensionless)
AC	=	Acres of riparian vegetation type

In this report, ET is summed by vegetation type and reach for LCRAS riparian data.

3.2 Data from HDB

Reclamation's HDB estimates and stores evaporation data from Lake Mead, Lake Mohave, and Lake Havasu using evaporation coefficients and lake elevations. It does not calculate evaporation or riparian ET losses along the Colorado mainstream. In HDB, daily reservoir surface areas are calculated from the area-capacity tables[10] and the average of the current and previous day's instantaneous midnight lake elevations, then multiplied by the standard evaporation coefficients specific to each month to estimate daily evaporation. Daily evaporation is summed to get monthly and annual evaporation.

The original evaporation coefficients used to calculate evaporative losses were based on pan evaporation studies. Those coefficients are still used to estimate evaporation at Lake Havasu. New evaporation coefficients for Lake Mead and Lake Mohave were recently developed from field data, evaluated, and then updated through a multi-year evaporation study performed by the USGS's Nevada Water Science Center in Boulder City, Nevada, and funded by Reclamation.

The goal of the USGS study was to determine new static monthly coefficients for calculating evaporation losses from Lake Mead based on the average monthly surface area. An Eddy Covariance station and a floating meteorological platform were set up on Lake Mead in March 2010 to collect sub-daily datasets of multiple physical parameters to accurately determine new static evaporation coefficients (average feet of evaporation per month) for Lake Mead. The USGS published an initial Scientific Investigations Report with the study's methodology and findings from March 2010 – February 2012 (Moreo & Swancar, 2013). In 2013, the study was expanded to collect data at Lake Mohave, the immediate downstream reservoir from Lake Mead,

[10] Lake Mead's area and capacity tables are available at https://www.usbr.gov/lc/region/g4000/LM_AreaCapacityTables2009.pdf.

using identical methods. The USGS published an Open File Report detailing the data collection and results for both Lake Mead and Lake Mohave from March 2010 – April 2019 (Earp & Moreo, 2021). At the time of this report, Reclamation continued to collaborate with the USGS to collect evaporation data at Lake Mead through the real-time Eddy Covariance station.

Reclamation's Boulder Canyon Operations Office performed sensitivity analyses and evaluated the impacts of the new evaporation coefficients on the daily, mid-term operations and long-term planning models, in accordance with Reclamation's Peer Review policy for influential scientific data (Reclamation, 2016). The new monthly evaporation coefficients replaced the values that were originally published in 1958 for Lake Mead using evaporation pans (Harbeck et al., 1958). The updated evaporation coefficients resulted in minimal impacts to projected elevations and operations tiers as simulated in the CRMMS deterministic 24-Month Study Model, the probabilistic runs using the CRMMS ensemble streamflow prediction (ESP) mode (known as CRMMS-ESP), and CRSS. Reclamation is continuing to monitor real-time evaporation at Lake Mead to better understand how evaporation is impacted by Lake Mead's declining elevation and regional climate change impacts. The evaporation coefficients will be revisited and adjusted in the future to incorporate the most recent trends.

The USGS evaporation study at Lake Mead and Lake Mohave resulted in a better understanding of the seasonality and magnitude of evaporation at two of the Lower Colorado Basin Region's largest reservoirs. With this information, the new evaporation coefficients were implemented in the operations models to provide the Colorado River Basin's management and stakeholders with model projections that incorporate the best available information[11]. For this report, the new evaporation coefficients were applied to the entire Lake Mead 2001 – 2021 dataset and the Lake Mohave 2017 – 2021 dataset since they provide a more accurate temporal distribution and evaporation magnitude at Lake Mead and Lake Mohave. The coefficients from the USGS study are provided in Appendix 5.

The methods deployed by the USGS were chosen based on the ability to deliver highly accurate monthly evaporation rates for each reservoir. For a more in-depth analysis regarding the energy budget methodology, instrumentation, and data collection results, the peer-reviewed Moreo & Swancar (2013) and Earp & Moreo (2021) USGS study reports are referenced. More in-depth analysis regarding the sensitivity analysis is available in the peer-reviewed Reclamation technical memorandum (Reclamation, 2022b).

3.2.1 Calculating Reservoir Evaporation

To calculate HDB evaporation from the lower Colorado River mainstream reservoirs, a daily surface area is estimated based on an average of the midnight reservoir elevations from the current and previous day, and the area-capacity tables. The daily surface area is then multiplied by the evaporation coefficient specific to each month (see Appendix 5). These calculations are performed on a daily time-step and the results summed to produce monthly and annual evaporation values. In this report, annual evaporation is reported on a calendar year basis

[11]The USGS coefficients were implemented in the CRMMS in April 2022, and in the CRSS in version 6, released in April 2023. More information on these models is available at: https://www.usbr.gov/lc/region/g4000/riverops/model-info.html#policy.

(January 1 – December 31). The following equation is used to calculate evaporation for a specific reservoir:

$$\text{HDB Reservoir Evaporation (AF)} = \sum_{t=0}^{n} \text{SA x } K_c$$

Where:

n = Timestep. A daily timestep is used to calculate reservoir evaporation in HDB. Daily values are summed to get monthly and annual evaporation estimates.

SA = Surface area (acres). The daily surface area is based on the average of the midnight reservoir elevations from the current day (t) and previous day (t – 1). The average daily reservoir elevation is converted to surface area using the reservoir specific area-capacity tables.

K_c = Evaporation coefficient (ft/day). Monthly coefficients in ft/month are provided in Appendix 5. The monthly coefficient is divided by the number of days in the month for use in daily calculations.

The new evaporation coefficients from the USGS study were applied to the Lake Mead and Lake Mohave HDB datasets in this report. The pan evaporation coefficients are still used at Lake Havasu and were used for this report. These results are summarized in Section 4.2 and provided in Appendix 3.

4 Mainstream Evaporation Losses

Evaporation losses in this report were calculated using two data sources, LCRAS and HDB. LCRAS provides data for Reaches 2 through 5, which includes the mainstream lower Colorado River and reservoirs, lakes, lagoons, and other backwater area surfaces below Hoover Dam to the NIB. The LCRAS data are summarized in Section 4.1. HDB provides evaporation data for only Lakes Mead, Mohave, and Havasu. HDB data are summarized in Section 4.2. Since evaporation data for Lake Mohave and Lake Havasu are available using both LCRAS and HDB, the data sources are compared in Section 4.3.

For purposes of this report, the evaporation data were divided into five reaches:

- Reach 1: Lake Mead
    - LCRAS data are not available for this reach.
    - Lake Mead evaporation data from HDB, using the USGS coefficients, are provided in Section 4.2.
- Reach 2: Hoover Dam to Davis Dam
    - LCRAS evaporation data are provided for this reach in Section 4.1. It includes evaporation from Lake Mohave.
    - Lake Mohave evaporation data from HDB, using the USGS coefficients, are provided in Section 4.2.
    - The LCRAS open water data and HDB data using the USGS coefficients are compared for Lake Mohave in Section 4.3.
- Reach 3: Davis Dam to Parker Dam
    - LCRAS data are provided for this reach in Section 4.1. It includes evaporation from Lake Havasu.
    - Lake Havasu evaporation data from HDB are provided in Section 4.2.
    - The LCRAS open water data and HDB data are compared in Section 4.3.
- Reach 4: Parker Dam to Imperial Dam
    - LCRAS open water data are provided for this reach in Section 4.1, which includes evaporation from reservoirs within the reach.
- Reach 5: Imperial Dam to the NIB
    - LCRAS open water data are provided for this reach in Section 4.1, which includes evaporation from reservoirs within the reach.

A map of the reaches is provided in Figure 1, on page ix. More detail on each individual reach is provided in maps included in Appendix 1.

4.1 LCRAS Open Water Data

LCRAS open water data are not available upstream of Hoover Dam, therefore this report only provides estimates of evaporation losses calculated using LCRAS data for Reach 2 through Reach 5.

These data are summarized annually from 2017 to 2021 in Table 6 below and are provided monthly in Appendix 2. Due to rounding to the nearest acre foot in the monthly data, the sum of the losses from each reach within a year may differ from the total value.

Table 6. Evaporation losses calculated using LCRAS open water data for Reach 2 through Reach 5.

Year	LCRAS Evaporation Loss (AF)				
	Reach 2	Reach 3	Reach 4	Reach 5	Total
2017	138,505	117,424	67,080	8,415	331,424
2018	144,980	123,179	66,535	8,254	342,948
2019	135,996	115,547	66,664	8,182	326,389
2020	146,212	124,224	70,748	8,535	349,719
2021	146,643	124,459	71,470	8,512	351,084
Average	142,467	120,967	68,499	8,380	340,313

4.2 HDB Data

Reservoir evaporation estimates are available from HDB for Lake Mead, Lake Mohave, and Lake Havasu. The evaporation coefficients for Lake Mead and Lake Mohave that are used in this report were updated in 2021, based on a Reclamation-funded USGS Study (USGS 2017). That study also estimated average annual evaporation at Lake Mead and Lake Mohave to be 6.22 ft and 5.64 ft, respectively. The evaporation coefficients for Lake Havasu were not updated in the USGS study. Monthly and annual data are provided in Appendix 3. Since Lake Mead's elevation and evaporation can vary significantly on an annual basis, Table 7 below summarizes the annual evaporation from Lake Mead for the period 2001-2021. Table 8 summarizes annual evaporation from Lake Mohave and Lake Havasu only for the period 2017-2021 as these reservoirs are maintained by a seasonal elevation guide curve, resulting in minimal annual variation in evaporation.

Table 7. Lake Mead annual evaporation losses using HDB with the updated 2021 USGS coefficients compared to elevation and average surface area.

Year	Low Elevation (ft)	High Elevation (ft)	Average Surface Area[12] (acres)	Evaporation (AF)
2001	1,178	1,197	136,049	842,089
2002	1,152	1,178	120,874	744,923
2003	1,139	1,155	109,477	678,240
2004	1,126	1,141	102,485	635,472
2005	1,130	1,148	106,124	661,620
2006	1,125	1,141	102,458	635,222
2007	1,110	1,130	96,616	598,044
2008	1,104	1,118	93,325	577,847
2009	1,093	1,113	89,460	553,559
2010	1,082	1,103	86,409	537,015
2011	1,086	1,133	91,971	577,495
2012	1,115	1,135	98,216	608,277
2013	1,104	1,123	93,649	580,228
2014	1,080	1,109	86,447	533,534
2015	1,075	1,089	83,054	515,859
2016	1,072	1,084	81,895	508,910
2017	1,079	1,090	83,826	521,725
2018	1,076	1,088	83,340	518,023
2019	1,081	1,090	84,587	523,928
2020	1,081	1,099	85,646	532,147
2021	1,065	1,087	80,771	500,743
Average	**1,103**	**1,122**	**95,080**	**589,757**
2017-2021 Average	**1,077**	**1,091**	**83,634**	**519,313**

[12] This is the annual average surface area at Lake Mead, calculated by utilizing the average daily surface area to obtain a monthly average surface area, which was subsequently averaged to provide the annual average surface area. A dynamic surface area is used for evaporation calculations in Reclamation's HDB, which is based on Lake Mead's elevation and the area and capacity tables: https://www.usbr.gov/lc/region/g4000/LM_AreaCapacityTables2009.pdf.

Table 8. Lake Mohave and Lake Havasu annual evaporation. Lake Mohave evaporation uses the 2021 USGS coefficients.

Year	Lake Mohave Evaporation (AF)	Lake Havasu Evaporation (AF)
2017	152,350	140,019
2018	151,592	139,506
2019	152,094	139,880
2020	151,489	139,047
2021	151,085	139,677
Average	**151,722**	**139,626**

4.3 Comparison of LCRAS and HDB Evaporation Data at Lake Mohave and Lake Havasu

A comparison of evaporation losses from the LCRAS open water data and HDB are provided in Table 9 for Lake Mohave and Table 10 for Lake Havasu. The same reservoir surface area was used in the calculations for both datasets. While the LCRAS data takes weather variations, such as temperature, into account, HDB calculates evaporation from the reservoir's elevation/surface area and evaporation coefficients previously calculated by Reclamation for these reservoirs.

The comparison in this section shows the difference between the LCRAS and HDB data at Lake Mohave, with an average 8% difference. At Lake Havasu, there is a more significant difference between LCRAS and HDB evaporation estimates, with an average difference of 35%. Use of Class-A Pan evaporation coefficients in HDB for Lake Havasu evaporation data likely contributes to the large difference. The update to Lake Mohave evaporation coefficients reduced the annual Mohave evaporation estimates in HDB from about 198 kAF per year to about 152 kAF per year, and concurrently reduced the percent difference between HDB and LCRAS data from about 26% to about 8% on average (based on data from 2017–2021). A similar trend could be expected at Lake Havasu if the evaporation coefficients were updated. In both cases, however, the LCRAS data provides a lower estimate of evaporation from the reservoirs compared to HDB.

Total mainstream evaporation and riparian ET losses are summarized in Chapter 6. Where LCRAS and HDB evaporation data overlap at Lake Mohave and Lake Havasu for Reach 2 and Reach 3, the LCRAS data are used to provide methodologically consistent data within the reach, as the values for the updated USGS coefficients are comparable. Since LCRAS data is not available for Reach 1, however, the Lake Mead HDB data are used in that reach.

Table 9. Comparison of evaporation losses at Lake Mohave.

Year	Average Surface Area (acres)	Evaporation (AF)		Percent Difference
		LCRAS	HDB	
2017	27,115	137,316	152,350	10%
2018	27,007	143,159	151,592	6%
2019	27,095	134,706	152,094	12%
2020	26,955	144,075	151,489	5%
2021	26,939	144,418	151,085	5%
Average	**27,022**	**140,735**	**151,722**	**8%**

Table 10. Comparison of evaporation losses at Lake Havasu.

Year	Average Surface Area (acres)	Evaporation (AF)		Percent Difference
		LCRAS	HDB	
2017	18,890	95,660	140,019	38%
2018	18,865	99,998	139,506	33%
2019	18,941	94,167	139,880	39%
2020	18,711	100,008	139,047	33%
2021	18,915	101,398	139,677	32%
Average	**18,864**	**98,246**	**139,626**	**35%**

4.4 Mainstream Evaporative Losses

Evaporative data produced by LCRAS were not available upstream of Hoover Dam, therefore this section presents HDB data for Reach 1 and LCRAS data from Reach 2 through Reach 5. LCRAS data were used for Reach 2 through Reach 5 to provide methodologically consistent data where available. The evaporative losses along the mainstream are presented in Table 11 below. While the 5 year period from 2017 to 2021 showed minimal variation in the evaporative losses for Reach 1, this reach can experience significant variations depending on Lake Mead's elevation and surface area, as shown in Table 7. The monthly and annual LCRAS data are provided in Appendix 2, and HDB data are provided in Appendix 3.

Table 11. Evaporation losses for Reach 1, using HDB, and Reaches 2 through 5, using LCRAS.

Year	HDB Evaporation Loss (AF)	LCRAS Evaporation Loss (AF)				Total Evaporation Loss (AF)
	Reach 1	Reach 2	Reach 3	Reach 4	Reach 5	
2017	521,725	138,505	117,424	67,080	8,415	853,149
2018	518,023	144,980	123,179	66,535	8,254	860,971
2019	523,928	135,996	115,547	66,664	8,182	850,317
2020	532,147	146,212	124,224	70,748	8,535	881,866
2021	500,743	146,643	124,459	71,470	8,512	851,827
Average	**519,313**	**142,467**	**120,967**	**68,499**	**8,380**	**859,626**

5 Riparian ET Losses

Riparian data produced by LCRAS were not available upstream of Hoover Dam, therefore this section only presents ET estimates from Reach 2 through Reach 5. The estimated riparian losses along the mainstream are presented in Table 12, as well as the associated acreage of riparian habitat within each reach. As shown in Figure 1 and the table below, Reach 4 contains the majority of the riparian habitats along the mainstream of the lower Colorado River resulting in increased riparian ET losses within that reach. The monthly and annual data for each riparian type that was described in Table 3 are provided in Appendix 4, including the associated acreage for each reach on an annual basis.

Table 12. LCRAS riparian ET losses and the average riparian acreage from Reach 2 through Reach 5.

Year	Riparian Loss (AF)				
	Reach 2	Reach 3	Reach 4	Reach 5	Total
2017	4,213	117,772	258,496	55,688	436,169
2018	4,438	123,876	256,681	54,799	439,794
2019	4,220	117,704	258,133	53,837	433,894
2020	4,490	125,177	271,644	55,561	456,872
2021	4,457	124,306	273,295	54,116	456,174
Average Loss	**4,364**	**121,767**	**263,650**	**54,800**	**444,581**
Average Riparian Acreage	**1,354**	**35,843**	**79,308**	**15,173**	**131,679**

6 Total Mainstream Evaporation and Riparian ET Losses

Estimates of the total system losses from both mainstream evaporation and riparian ET are presented in Table 13.

Reach 1 only includes Lake Mead evaporation estimates from HDB data that were presented in Section 4.2. LCRAS data are not available upstream of Hoover Dam and riparian ET data for Reach 1 are not available from current Reclamation datasets. As described in Section 3.2, HDB evaporation estimates use standard monthly evaporation coefficients, so any variation from year to year is dependent on reservoir elevations. Variation in the Reach 1 data from year to year is due to changes in Lake Mead's elevation, resulting in changes to the surface area.

Data in Table 13 for Reach 2 through Reach 5 are the combined annual LCRAS evaporative losses, presented in Section 4.1, and the annual riparian ET losses for Reach 2 through Reach 5 as presented in Chapter 5. Where LCRAS and HDB evaporation data overlap at Lake Mohave and Lake Havasu, the LCRAS evaporation data are used to ensure consistency in the methodology applied for the whole reach. As described in Section 3.1, LCRAS evaporation and riparian ET estimates are based on open-water and riparian acreages, and daily evaporation and ET rates that incorporate weather data. Variation in the Reach 2 through Reach 5 estimates from year to year is due to changes in the acreages and weather conditions.

Table 13. Total losses (evaporation and riparian ET) from Reach 1 through Reach 5.

Year	Mainstream Evaporation and Riparian ET Losses (AF)					
	Reach 1	Reach 2	Reach 3	Reach 4	Reach 5	Total
2017	521,725	142,718	235,196	325,576	64,103	1,289,318
2018	518,023	149,418	247,055	323,216	63,053	1,300,765
2019	523,928	140,216	233,251	324,797	62,019	1,284,211
2020	532,147	150,702	249,401	342,392	64,096	1,338,738
2021	500,743	151,100	248,765	344,765	62,628	1,308,001
Average	**519,313**	**146,831**	**242,734**	**332,149**	**63,180**	**1,304,207**

7 Summary

The LCRAS and HDB datasets available for the lower Colorado River mainstream were used in this study to estimate the total annual evaporation and riparian ET losses from the mainstream of the lower Colorado River, including mainstream reservoirs, between Lake Mead and the NIB. This study showed that over the 5-year period from 2017 to 2021, the average annual total losses from open-water evaporation and riparian ET exceeded 1.3 million acre feet. As can be seen in Table 14 and Figure 2, below, the majority of those estimated system losses come from the major reservoirs in Reach 1, Reach 2, and Reach 3, contributing almost 760 kAF of total evaporative loss. Furthermore, most of the reservoir evaporation occurs from Lake Mead, Reach 1, with an average loss of almost 520 kAF annually, although this value varies significantly as the reservoir elevation and surface area fluctuates. Average mainstream evaporation from the Colorado River accounts for less than 8% of the total estimated average system losses. More than half of the estimated riparian ET occurs in Reach 4, between Parker and Imperial Dam.

Table 14. Summary of 2017-2021 average annual losses, in AF, for the lower Colorado River, major reservoirs and riparian ET by reach and in total.

Type of Loss	Reach 1	Reach 2	Reach 3	Reach 4	Reach 5	Total
Mainstream Evaporation (2017-2021 Avg)	N/A	1,732	22,721	68,499	8,380	101,332
Major Reservoir Evaporation (2017-2021 Avg)	519,313	140,735	98,246	N/A	N/A	758,294
Riparian ET (2017-2021 Avg)	N/A	4,364	121,767	263,650	54,800	444,581
Total Losses (2017-2021 Avg)	**519,313**	**146,831**	**242,734**	**332,149**	**63,180**	**1,304,207**

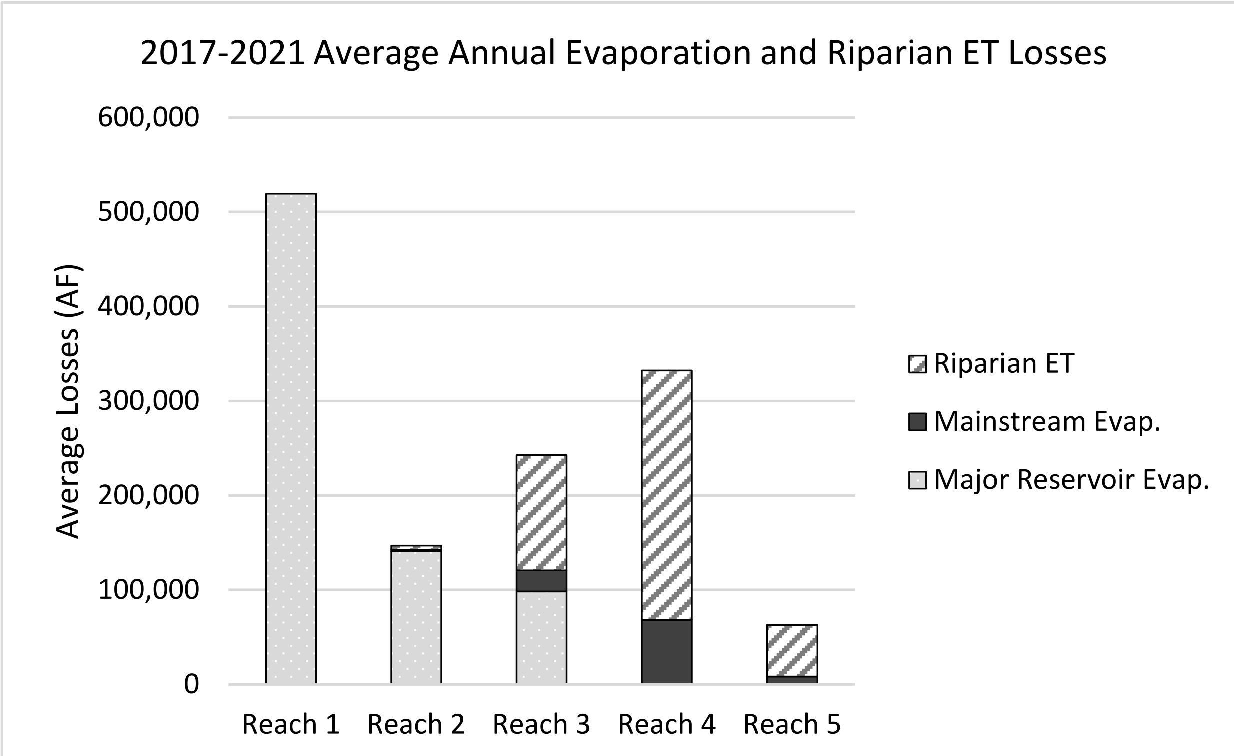

Figure 2. Chart of 2017-2021 average annual losses, in AF, for the lower Colorado River major reservoirs, mainstream evaporation, and riparian ET by reach.

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