
**Phase II Report of
Matthew J. Tonkin, PhD**

**Evaluation of the Safe Yield and Storage
Properties of the Indian Wells Valley (IWV)
Basin, California**



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Appendix A. Curriculum Vitae

Acronyms

%	percent
3D	three-dimensional
AEM	Airborne Electro-Magnetic
AF	acre-feet
AFY	acre-feet per year
BCM	Basin Characterization Model
DWR	California Department of Water Resources
ET	evapotranspiration
GSA	Groundwater Sustainability Agency
GSP	Groundwater Sustainability Plan
HCM	hydrogeological conceptual model
HGZ	hydrogeologic zone
IWV	Indian Wells Valley
LAA	Los Angeles Aqueduct
LSM	land surface model
MAF	million acre-feet
MBR	mountain block recharge
MFR	mountain front recharge
OSU	Oregon State University
PRISM	Parameter-elevation Regressions on Independent Slopes Model
SGMA	Sustainable Groundwater Management Act
SSP&A	S.S. Papadopoulos & Associates, Inc.
TDS	total dissolved solids
TWG	Indian Wells Valley Technical Working Group
USGS	United States Geological Survey
WY	water year

Executive Summary

I have been retained to provide scientifically rigorous estimates of the safe yield of the Indian Wells Valley (IWW) Basin and of the volume of groundwater stored in the IWW Basin, and to review and evaluate the analyses and opinions provided by any other experts on these topics. As a result of the technical analyses detailed in this report, **I have formed the following opinions:**

- 1. Opinion 1: The Main Features and Processes of the Hydrogeological Conceptual Model (HCM) are Well Characterized.**
- 2. Opinion 2: The Groundwater Model Developed by Ramboll Provides a Reliable Representation of the IWW Basin HCM.**
- 3. Opinion 3: The Rates and Locations of Recharge have Been Quantified using Land Surface Process Modeling and Groundwater Modeling.**
- 4. Opinion 4: The Rates and Locations of Evapotranspiration have Been Quantified using Groundwater Modeling.**
- 5. Opinion 5: The Safe Yield of the IWW Basin Has Been Quantified using Groundwater Modeling and is Corroborated by Estimates Obtained using Other Methods.**
- 6. Opinion 6: The Quantity of Water Available in Storage Has Been Quantified using Groundwater Modeling and is Corroborated by Estimates Obtained using Other Methods.**

This report proceeds as follows:

- **Section 1** provides a summary of my opinions.
- **Section 2** of my background, assignment, and methods.
- **Section 3** describes the study area and its water resources, and describes other studies of the recharge, discharge, storage, and yield, of the IWW Basin.
- **Section 4** details the steps that my team and I undertook to develop my estimates of safe yield and of aquifer storage for the IWW Basin and compares my estimates with values reported by others. Because groundwater modeling was used as a basis for the yield and storage calculations, this section also describes this modeling.
- **Section 5** provides recommendations that could improve basin hydrologic studies and yield estimates.

- **Section 6** lists the documents and other materials that I reviewed or relied upon in preparing this report and forming my opinions.

Qualifications of Opinions

I understand that other experts may develop opinions and yield estimates and may use modeling or other methods to support those opinions. If other experts do develop opinions, I would want to understand the basis for their opinions, and I would need to study any models that they relied upon, as well as any other materials relied upon by any other experts in this matter, in adequate depth to formulate updated opinions, if necessary.

Section 1.

Summary of Opinions

Based on the analyses and calculations presented in this report, together with my professional and academic experience, I have reached the following opinions about the quantities of groundwater available in the IWV Basin. I hold these opinions to a reasonable degree of scientific certainty, though they are subject to change pending further review of existing and new documents and data.

Opinion 1. The Main Features and Processes of the Hydrogeological Conceptual Model (HCM) are Well Characterized.

The main hydrogeological features and processes of the IWV have been determined using state-of-the-art methods and data including Airborne Electro-Magnetics (AEM), seismic surveys, deep borings, and long-term monitoring of groundwater levels and stream flows. This characterization provides a reliable basis for the groundwater flow model developed by Ramboll. **Section 3** of this report summarizes the hydrogeological conceptual model of the IWV Basin and presents a conceptual water budget that demonstrates that the safe yield of the IWV Basin can be determined as the difference between the rates of groundwater recharge and discharge excluding pumping.

Opinion 2. The Groundwater Model Developed by Ramboll Provides a Reliable Representation of the IWV Basin HCM.

The design, structure, inputs, parameterization, and calibration of the groundwater model developed by Ramboll (Ramboll Model) incorporates the best available information to represent the major features and processes of the HCM. These inputs render the Ramboll Model suitable for use in evaluating water resources and estimating safe yields. **Section 4** of this report describes the design, construction, and inputs of the Ramboll Model, and presents outputs from the calibrated model.

Opinion 3. The Rates and Locations of Recharge have Been Quantified using Land Surface Process Modeling and Groundwater Modeling.

Groundwater recharge to the IWV is dominated by Mountain Front Recharge (MFR) processes including run-off and underflow from the Sierra Nevada and other basin-margin mountains with additional contributions from inter-basin flow; return water from irrigation;

leakage from water mains; and occasional releases from the Los Angeles Aqueduct (LAA). Reliable estimates of natural recharge via MFR processes have been determined using the Basin Characterization Model (BCM), a tool developed specifically for estimating run-off and recharge in semi-arid environments including California mountain-bounded basins. **Section 4** of this report summarizes the estimated rates and locations of groundwater recharge for use in safe yield calculations. **Section 4** also presents my yield calculations based on these recharge rates.

Opinion 4. The Rates and Locations of Evapotranspiration have Been Quantified using Groundwater Modeling.

The primary natural groundwater discharge mechanism is ET which combines evaporation from dry lake beds with transpiration via vegetation. These ET processes are focused along arroyos in the valley floor and the evaporative playa at the core of the IWV Basin. As water levels have declined, ET rates within the valley floor have declined—a feature that is described in previous studies and was verified by groundwater modeling. Some studies—including a US Navy-led de-designation application—suggest that under present day conditions ET processes draw water from a “perched zone” that is not connected to and does not discharge from the regional groundwater system. **Section 4** of this report summarizes the estimated rates of ET use in safe yield calculations. In **Section 4** I provide yield estimates including and excluding ET recognizing there is uncertainty regarding the connection to the regional groundwater system.

Opinion 5. The Safe Yield of the IWV Basin Has Been Quantified using Groundwater Modeling and is Corroborated by Estimates Obtained using Other Methods.

I have used the Ramboll Model to calculate the safe yield of the IWV Basin as the difference between the average rates of groundwater recharge and average rates of groundwater discharge excluding pumping. I estimate the *total* safe yield to be 14,375 acre-feet-per year (AFY). This estimate does not account for ET. Because I recognize that there is uncertainty regarding the demand that ET makes on regional groundwater, I present a lower estimate for the yield that includes ET. **Section 4** of this report presents my yield estimates, and their basis, and compares my estimates with estimates made by others.

Opinion 6. The Quantity of Water Available in Storage Has Been Quantified using Groundwater Modeling and is Corroborated by Estimates Obtained using Other Methods.

I have used the Ramboll Model to calculate the volume of groundwater that is stored within the aquifers of the IWV Basin. I estimate the total volume of groundwater in storage to be about 51 million acre-feet (MAF). Not all of this water is of potable quality as I describe in **Section 3** and **Section 4**, which presents my calculations for estimating the quantity of groundwater stored within the IWV Basin and compares my estimate with estimates made by others.

Section 2.

Introduction

2.1 Overview

I am the President and a Principal Hydrogeologist at S.S. Papadopoulos & Associates, Inc. (SSP&A), where I have been employed for 30 years. I specialize in evaluating a wide range of information and data types to support groundwater and surface water resource and contamination studies. My expertise includes planning field data collection activities; evaluating a broad range of environmental data; and developing, calibrating, and applying, computer models. Several of my projects in recent years have emphasized the evaluation of groundwater and surface water resources to interpret the impact of natural and anthropogenic stresses on resource availability.

I have completed a variety of projects under contract to the California Department of Water Resources (DWR) over 20 years, focused on the analysis and modeling of groundwater resources, including the development of public-domain and open-source methods and codes to facilitate those analyses. I have been on the organizing committee of the MODFLOW and More conference series since 2011, now hosted through Princeton University. I hold a Ph.D. degree from the University of Queensland, Australia, on the topic of model calibration and uncertainty analysis. I have authored peer-reviewed articles and taught professional courses on groundwater modeling, model calibration, and related topics. In my capacity as SSP&A President, I am exposed to and advise on a wide variety of projects nationwide and internationally.

I have been previously retained to provide expert opinion, and I have been deposed and provided testimony at trial in some of those matters. A copy of my curriculum vitae, with a list of publications that I have (co-) authored and a list of matters in which I have testified, is provided as **Appendix A** to this report. SSP&A is compensated at the hourly rate of \$376.00 per hour for my engagement in this matter.

2.2 Background

Most water supply for use within the IWV Basin (Basin Number 6-054) is obtained by withdrawing (pumping) groundwater from a thick sequence of unconfined and confined aquifers. Although the sequence of geologic units within the IWV Basin is very thick—

extending to a depth of 7,000 feet—pumping has reduced groundwater levels and at times depleted storage. The depletion of storage has the potential to threaten the sustainability of the basin water resources. The groundwater resources of the IWV Basin—including the locations and rates of recharge and discharge—have been studied by numerous state and federal agencies as well as the local water district over many decades. These studies have included the development of land-surface process models to estimate recharge to the basin and the development of groundwater flow models to estimate water availability and support resource management decisions.

2.3 The Sustainable Groundwater Management Act (SGMA) and Safe Yield

The California Sustainable Groundwater Management Act (SGMA; 2014), aims to manage groundwater resources sustainably. SGMA requires local agencies to form groundwater sustainability agencies (GSAs) which are tasked with developing and implementing groundwater sustainability plans (GSPs) to avoid undesirable results over a 20-year implementation period. The key undesirable results—which do not apply equally to every basin—are (a) chronic lowering of groundwater levels, (b) significant and unreasonable reduction of groundwater storage (i.e., “overdraft”), (c) significant and unreasonable seawater intrusion, (d) significant and unreasonable degraded water quality, (e) significant and unreasonable land subsidence, and (f) depletion of interconnected surface water.

The DWR categorized the IWV Basin as subject to critical conditions of overdraft (DWR Bulletin 118 Interim Update, 2016), and the IWV Basin has been categorized as a High Priority Basin under SGMA. With regard to storage, and determination of overdraft, SGMA states that:

“Overdraft during a period of drought is not sufficient to establish a chronic lowering of groundwater levels if extractions and groundwater recharge are managed as necessary to ensure that reductions in groundwater levels or storage during a period of drought are offset by increases in groundwater levels or storage during other periods.”

The 2020 GSP for the IWV Basin (IWVGA, 2020) estimates that the basin is in overdraft by 400% for the years 2011-2015. For the purposes of my work the chronic lowering of groundwater levels and unreasonable reduction of storage are the primary undesirable results. As an inland basin, the IWV Basin is not subject to seawater intrusion; however, the

freshness (i.e., usable or potable quality) of groundwater declines within increasing depth in the basin, and some shallow areas of the basin—principally near and beneath the evaporative playa of China Lake—exhibit elevated concentrations of salts due to evaporation and other factors.

A definition for the (total) safe yield of a groundwater basin was provided by the California Supreme Court as follows:

“... the maximum amount of water that can be withdrawn annually, from a groundwater supply under a given set of conditions, without causing an undesirable result.” (Supreme Court of California, 1975, City of Los Angeles v. City of San Fernando).

The total safe yield can be discretized into native and non-native components or fractions, where the native fraction derives from naturally occurring or naturally sourced recharge—such as rainfall—and the non-native fraction derives from anthropogenic sources of recharge, such as water imported from another basin.

2.4 My Assignment

My assignment in this matter is to:

- Provide a scientifically rigorous estimate of the safe yield of the IWV Basin.
- Provide a scientifically rigorous estimate of the volume of groundwater stored in the IWV Basin.
- Review and evaluate the opinions provided by any other experts in this matter and—if necessary—prepare responsive opinions.

2.5 Methods

The technical challenges in this matter relate to the presence and availability of usable water stored in the subsurface. To complete this work, my team and I commenced by reviewing and analyzing the following documents, data, and other information:

- General publicly available and site-specific reports and studies on the hydrology, hydrogeology, land use, and other characteristics of IWV Basin and surrounding area;
- Reports and studies describing the locations, mechanisms, and rates of natural recharge and discharge;

- Site-specific studies describing historical water-resources development, irrigated agriculture, groundwater withdrawals, and groundwater level declines;
- Reports describing the development and application of models of groundwater recharge and groundwater flow;
- Available data on climate and streamflow along the IWW Basin margins; and,
- The GSPs for the IWW Basin (IWWGA, 2020) and its first periodic evaluation (IWWGA, 2025).

Following these reviews and data analyses, my team and I reviewed, executed, made modifications to, and calculated water budgets using the groundwater model of the IWW Basin developed by Ramboll (the “Ramboll Model”).

The analyses and opinions presented in this report are based upon review of the documents cited in **Section 6** together with calculations made using the Ramboll Model and the U.S. Geological Survey (USGS) Basin Characterization Model (BCM: Flint et al, 2021a,b). As is common practice for any modeling study, I evaluated the fitness of these models before using them to develop opinions. The methods used are consistent with my professional and academic practice in assessing the presence, distribution, availability, and utilization of groundwater and surface water.¹

¹ The documents cited in Section 6 of this report and/or produced as part of my reliance materials, along with knowledge gained from professional and academic practice, constitute the facts and data I have considered in forming my opinions. I may use any of the documents, tables, figures, or appendices in this report as exhibits to support my opinions in any testimony I may give in this matter. If I discover that I inadvertently omitted any such material—and presently, I am aware of no such omissions—I will promptly provide it.

Section 3.

Study Area Overview and Water Resources

This section describes general conditions within and surrounding the IWV Basin. Much of the discussion is drawn from previous publications by the USGS and other publicly available materials.

3.1 Overview of Water Resource Concepts

Fresh water is a critical resource that occurs in rivers and lakes—where it is referred to as surface water—and in the subsurface, where it is referred to as groundwater. Groundwater and surface water are linked as part of the hydrologic cycle. An aquifer is a body of rock that can store and transmit groundwater. Aquifers can have very different characteristics from each other and as a result are not equally prolific or reliable. The ability of an aquifer to provide a sustainable supply depends upon both water storage and water movement (transmission) properties, in addition to the long-term rate of recharge that the aquifer receives.

Aquifers are recharged (a) via the land surface, when water derived from precipitation—in the form of rainfall, snow, or fog—and water that leaks from streams seeps into the ground and (b) in the subsurface by the influx of groundwater from adjacent connected basins. When the rate of groundwater withdrawal via pumping exceeds the *net* rate of groundwater recharge—i.e., the difference between natural recharge and discharge rates—groundwater levels fall. The terms “groundwater overdraft” and “groundwater mining” are often used to describe the condition where groundwater use exceeds available recharge for a sufficiently extended period of time that water levels continue declining.

The characteristics of geologic materials that comprise aquifers vary widely, which results in very different potential to yield sustainable supplies. Geologic materials are often distinguished as comprised of either consolidated rock or unconsolidated sediment. Consolidated rock typically consists of very old sediments that have undergone compaction and cementation – such as sandstone and shale – or of igneous rocks derived from volcanic activity such as granite and basalt. In contrast, unconsolidated sediments contain loose granular material such as sand, gravel, and silt. Unconsolidated deposits are typically formed of material derived from the disintegration and transport of consolidated

rocks—such as via river transport. Unconsolidated sedimentary deposits are underlain everywhere, at varying depths, by consolidated rock.

The amount of water that an aquifer can hold or store depends upon the size of the aquifer and the properties of the geologic formations. Aquifer storage depends on the aquifer “porosity”—that is, the volume of “pore space” which in unconsolidated sediments is the space between the grains, and in consolidated rock it is the combination of fractures plus any open space remaining from the consolidation process. As the proportion of pore space decreases, storage and transmission properties diminish, and the viability of the aquifer for water supply lessens.

Groundwater present in unconsolidated sediments such as gravel, sand, and silt, occurs and moves within the pore space between the grains. This space between grains is referred to as “primary porosity”, which also identifies that the voids formed at the same time as the rock. In contrast, because many consolidated rocks have undergone compaction and cementation, there is very little “primary porosity” to store and transmit water. Rather, tectonic activity may cause consolidated rocks to deform which results in discrete fractures and faults. It is within these fractures and faults—which are referred to as “secondary porosity” features—within consolidated aquifers, that groundwater occurs and moves. The term “secondary” also identifies that the voids formed sometime after the rock was formed. The rate of groundwater movement also depends on the amount and type of pore space, and how well the pore space is connected.

Groundwater stored within aquifers occurs under two different conditions: unconfined and confined. The top surface of an unconfined aquifer is often referred to as a phreatic surface, and it is the location where pore water pressure equals atmospheric pressure. This is also referred to as the water table, and the term “water table aquifer” is sometimes used to refer to unconfined aquifers. When a well is drilled into an unconfined or “water table” aquifer, the water level within the well is at the same elevation as the top of the aquifer; the water level in the well defines the top of the aquifer. In contrast, a confined aquifer is overlain by less permeable material that restrict the vertical movement of water. A confined aquifer does not possess a phreatic surface because the water is stored under pressure. When a well is drilled into a confined aquifer, the water level within the well rises *above* the top of the aquifer and defines the pressure elevation within the aquifer, but it does not coincide with or define the physical top of the aquifer. If the pressure within the

confined aquifer is great enough, the well may flow at the surface without pumping, in which case it is referred to as “artesian”.

In groundwater studies, the terms “open” and “closed” are often used to distinguish aquifer systems and basins—where “open” systems continuously interact and exchange with adjacent systems and “closed” systems undergo negligible interaction. This distinction helps distinguish very interactive basins from those that are less so, however, there are few genuinely closed basins where there is no exchange of water with adjacent basins. Features such as faults and transitions in material properties may reduce the (otherwise unimpeded) flow of water between basins but rarely reduce it to zero. Anthropogenic stresses such as pumping can change a basin’s relationship to its neighbors: for example, a system that outflowed under natural conditions may, when pumped, cease to outflow and instead draw water from adjacent systems.

Lastly, groundwater can occur as part of a broad-scale and connected system—in which case it is usually referred to as a regional aquifer—or it can occur within a local system that is vertically above, and separated from, the regional aquifer. The latter is referred to as a “perched” aquifer, which forms on a relatively impermeable layer that inhibits the vertical migration of water to the regional system.

3.2 Study Area Physiography and Climate

The IWV Basin is an arid north–south oriented basin located in east-central California, south of the Central Valley. According to DWR California’s Groundwater Bulletin 118 (DWR, 2004, 2016), the IWV Basin (Basin #6-054) has a surface area of about 382,000 acres (597 square miles) and lies within Inyo, Kern, and San Bernardino counties, California (**Figure 3-1**). The Sierra Nevada Range bounds the IWV Basin to the west, the Coso Range to the north, the Argus Range to the northeast, and the El Paso Mountains to the south (**Figure 3-2**).

The IWV Basin is described by the DWR (Bulletin 118, 2004; 2016) as “*an internally drained basin bounded by outcrop of igneous and metamorphic basement rock complexes*” and is often interpreted as being a closed basin. However, the possibility of inter-basin flow via connected alluvium and fractured rock has been recognized in numerous studies; for example, Dutcher and Moyle, Jr. (1973) describe the IWV Basin as “almost closed” due in part to evidence for inter-basin flows. Approaching the center of IWV Basin from its margins, coalescing alluvial fans grade into playas where ground water discharges via ET

(Dutcher and Moyle, Jr., 1973). China Lake playa is situated in the central northeastern valley and is the primary natural groundwater discharge point via ET (see for example, Bean, 1989).

The GSP (IWVGA, 2020) describes the IWV Basin as “*part of the Mojave Desert and has an arid, high desert climate characterized by hot summers, cold winters, and irregular and sparse precipitation.*” Summer high temperatures on the playa are typically over 100 degrees Fahrenheit (°F) with winter lows typically in the 20s and 30s °F. The average annual recharge from direct rainfall is expected to be small, and indeed precipitation on the valley floor is described as typically ranging from 2 to 5 inches per year (in/yr), with snowfall in December and January (IWVGA, 2020). The GSP (IWVGA, 2020) also describes the presence of high ET rates—particularly in the valley floor, and to a lesser extent within the mountainous areas surrounding the basin—resulting from the combination of high temperatures, high winds, and low humidity.

In contrast, the GSP (IWVGA, 2020) and other studies indicate that the surrounding mountain areas receive substantially more precipitation than the valley floor—in the form of both rainfall and snowfall—and as a consequence it is this precipitation forms the primary source of recharge to the IWV Basin via MFR (also referred to as mountain block recharge [MBR]). Numerous small intermittent streams in the canyons of the Sierra Nevada convey runoff to the IWV Basin alluvial fans where—after crossing the Sierra Nevada frontal fault zone—downward seepage can recharge the underlying groundwater. Although these MFR processes may be most prevalent along the Sierras, contributions of MFR to IWV Basin also arise from recharge and runoff from the Argus Range, El Paso Mountains, and also from surface runoff and inter-basin flow from Rose Valley at Little Lake (**Figure 3-2**).

3.3 Hydrogeology and Water Resources of the IWV Basin

3.3.1 Hydrogeology

The IWV Basin is an extension of Owens Valley—located to the north—separated by the recent volcanics of the Coso Range. The IWV Basin is defined by faults to the west and to the south and is crosscut by additional faults that exhibit predominantly northwest and northeast strikes. The IWV Basin consists of two areas: China Lake forms the central and northern area, and the El Paso area lies to the southwest. The basin experienced a complex geological evolution. In June 2019 Ramboll issued a final report of their study of the hydrogeology of the IWV Basin, entitled “*Hydrogeologic Conceptual Framework - Indian Wells Valley*” (the HCF: Ramboll, 2019), which was prepared for Indian Wells Valley Water

District (IWWVD) and the Brackish Groundwater Resources Study Group (BGRSG). This HCF provides an extensive review of historical studies of the IWV Basin; what follows below is an abbreviated overview of the main features and processes of concern to this yield analysis.

The IWV Basin formed as a half-graben from downward movement on the west side of the China Lake area along the Sierra Nevada frontal fault. The vertical displacement on this fault is on the order of 3,000 meters (Monastero et al., 2002), which resulted in a “wedge” of sediment accumulation within the IWV Basin. On the west side of the China Lake area over 7,000 feet of valley fill sediments accumulated, thinning to about 2,000 feet to the east (Ramboll, 2019; Ramboll, 2025) (**Figure 3-3**). The presence of more recent alluvial fans along the IWV Basin perimeter and extending into the basin floor facilitates the infiltration of water derived from precipitation within the mountain ranges. As described by Ramboll (2019; 2025):

“The Basin floor is flanked by a series of broad coalescing Pleistocene-age pediments and recent alluvial fans and drainages (Rosenthal et. al. 2017). On the western and southern sides of the valley, these low-gradient fans extend for several kilometers into the basin. Along the northwestern edge of the valley, distal portions of the eastward-oriented fans are truncated by a complex of well-defined channels and ephemeral washes that mark the former course of the ancestral Owens River.”
(Figure 3-4)

Figure 3-5 presents a conceptual diagram of a mountain front (or mountain block) that abuts sedimentary basin fill similar to that which forms the IWV Basin. In this schematic, both conformable and non-conformable—i.e., fault-controlled—contacts can be seen between the basin fill sediments and the underlying and abutting bedrock. Different components of MFR (MBR) are shown in this figure—including surface infiltration through the basin fill from a mountain-sourced stream; focused MFR/MBR, which occurs through faults and fracture zones or beneath mountain-sourced streams; and diffuse MFR/MBR, which occurs widely across the mountain front. In the arid setting of the IWV Basins, these mountain front processes provide the predominant supply of recharge to the aquifer.

Understanding of the thickness, properties, and connectivity of the California’s groundwater basins is a primary concern to the DWR. In line with this, the DWR established a Basin Characterization Program to develop and distribute data and information about California’s groundwater basins to help local communities better understand their

aquifers. One of the major projects managed under the Basin Characterization Program is the completion of statewide AEM surveys. The AEM project provides state and federal agencies, GSAs, stakeholders, and the public with geophysical data, tools, and analyses derived from AEM surveys conducted in California’s high- and medium-priority groundwater basins. As stated by the DWR:

“The collected AEM data assists local water managers in characterizing their aquifer systems and supports the implementation of the Sustainable Groundwater Management Act (SGMA) to manage groundwater for long term sustainability.” (More information can be found in the AEM Proposition 68 Fact Sheet, DWR, 2020b).

The data obtained from these AEM surveys is intended to help refine understanding of and thereby update delineations and properties of aquifers; develop or refine HCMs; prioritize areas that are most suitable for managed aquifer recharge (MAR); and parameterize groundwater models developed to support such projects. Integration of these AEM survey data is ongoing in many basins, and Ramboll (2019, 2025) is actively incorporating these data into the Ramboll Model detailed in **Section 4** of this report.

3.3.2 Water Resources

Groundwater supplies over 95% of water used in IWV Basin (Ramboll, 2025). According to DWR Bulletin 118 the primary groundwater-bearing formations of the IWV Basin are Pleistocene to Holocene age lakebed, stream, and alluvial fan, deposits. These unconsolidated deposits make up an upper aquifer and a lower aquifer. From DWR (Bulletin 118):

“The lower aquifer is the primary producer for this basin (Berenbrock and Martin, 1991). The upper aquifer underlies a portion west of China Lake towards the center of the Valley and an area southward into the community of China Lake (Kunkel and Chase 1969). The base of this aquifer is not well defined, the aquifer does not yield water freely to wells, and consists of poor quality water (Berenbrock and Martin, 1991). The lower aquifer is much larger, with a saturated thickness of up to 1000 feet in the central part of the valley (Kunkel and Chase, 1969). The lower aquifer is considered unconfined except in the eastern part of the valley where the aquifer is confined by silt and clay lenses, lake deposits, and playa deposits. Specific yields used for calculating storage capacity have ranged from 10 to 20 percent but may be somewhat lower (Bean 1989).”

Under natural conditions, groundwater generally would flow through the lower aquifer from the areas of recharge along the basin margins toward China Lake, where it would flow from the lower aquifer to the upper aquifer to discharge (DWR Bulletin 118). However, previous studies have noted that groundwater levels in the basin have been declining for several decades. As a result, groundwater flow patterns have altered (e.g., Warner, 1975).

As outlined above, recharge to the IWV Basin stems primarily from precipitation in the surrounding elevated areas. As noted by Lee (1912; at page 409), “*The annual variations in precipitation are characterized by great extremes.*” There can be multiple consecutive years of above-average or below-average conditions; this observation is corroborated by more recent observations of precipitation obtained from the PRISM group at Oregon State University (OSU)—where PRISM stands for “*Parameter-elevation Regressions on Independent Slopes Model*” (**Figure 3-6**). PRISM data have been made available by OSU for evaluating climate conditions since the mid-1990s and provide a comprehensive nationwide database of climate data that are often used as inputs (or “forcing data”) to groundwater models. PRISM provides an important source of input climate data to the Ramboll Model described in **Section 4** of this report.

In addition to the natural recharge described above, there are several sources of anthropogenic recharge that results from human interaction with the environment. These anthropogenic sources of water include irrigation return flows, un-gaged water mains leakage, un-gaged leakage from the Los Angeles Aqueduct (LAA), periodic releases from the LAA, and percolation from wastewater treatment ponds. The final source of additional water to the IWV Basin arises from geothermal upwelling—however, I have not evaluated this component in my work as the quality of geothermal water is usually not suitable for most uses.

Groundwater discharge from the IWV Basin primarily occurs via (a) pumping and (b) ET. As water resources have been developed over time, groundwater pumping has become the dominant discharge mechanism. Groundwater pumping has been the largest cause of groundwater discharges from the basin for over 50 years (Ramboll, 2025) (**Figure 3-7**). Previous studies offer different perspectives regarding whether the regional aquifer or a localized and essentially isolated aquifer is the source of water that meets the ET demand throughout much of the floor of the valley. This topic—and its impact on yield estimates—is discussed in **Section 4**, together with discussion on the estimated quantities of pumping and discharge via ET.

3.3.3 Water Quality

Groundwater in the IWV Basin is of variable quality. DWR (Bulletin 118, citing Berenbrock and Martin, 1991) notes that water within the upper aquifer—which underlies a portion west of China Lake towards the center of the Valley—is generally of poor quality; and states that the lower aquifer is the primary aquifer because it has better water quality. Dutcher and Moyle, Jr. (1973) provide the following instructive narrative regarding groundwater quality in the IWV Basin:

“Ground water in the valley may be grouped by chemical quality into three general categories. The first category, the water of best quality, occurs in the alluvial deposits of shallow to medium thickness in the western and northwestern parts of the valley. The dissolved-solids content of the water there is generally less than 600 mg/l (milligrams per liter), the hardness 100-200 mg/l, chloride less than 100 mg/l, and boron and fluoride each less than 1 mg/l. Water of the second category occurs mainly in the deep zones in the central and south-central part of the basin, and, perhaps, in the deep deposits in the western part of the basin. The dissolved-solids content is also generally less than 600 mg/l, the percent sodium is about 65-99, boron commonly between 3 and 10 mg/l, and fluoride 1-4 mg/l. In water of the third category, sodium and chloride ions are dominant. This water occurs in the shallow deposits beneath the playa areas. The dissolved-solids content is more than 1,000 mg/l and chloride is more than 250 mg/l; locally the chloride ion content exceeds 3,000 mg/l.”

The DWR (Bulletin 118) note that the development of groundwater within the IWV Basin also led to changes that could exacerbate existing groundwater quality concerns:

“As a result of pumping, a regional cone of depression has formed approximately three miles northwest of the City of Ridgecrest (Berenbrock 1987). Hydraulic heads have changed in the shallow aquifer, due to effluent recharge, causing it to leak into the deep aquifer and migrate towards the cone of depression (Bean 1989). This leakage is of concern because of the shallow aquifer’s historically poor water quality.”

3.4 Previous Water Budget Studies and Yield Estimates

Appendix A to the “Assessment of Safe Yield for the Indian Wells Valley Groundwater Basin” prepared by the Indian Wells Valley Technical Working Group (IWVTWG or just TWG) (2024a) summarizes previous estimates of safe yield and related studies for the IWV Basin. What follows below is a synopsis of historical studies.

The earliest published estimate of recharge is probably provided by Lee (1912) who states that *“The canyons most productive of run-off are along the slopes of the Sierra Nevada, such as Five Mile, Nine Mile, Sand and Grapevine.”*, and goes on to estimate that *“The total run-off from the 360 square miles of mountain drainage directly tributary to Indian Wells Valley, measured at mouth of canyons, probably would not exceed 37 second-feet continuous flow or 27,000 acre-feet per-annum.”* More recently, Dutcher and Moyle, Jr. (1973) provide the following estimates of recharge, ET, and available yields, for the IWV Basin:

“The maximum developable yield of Indian Wells Valley ground-water basin, under existing conditions, is estimated to be 10,000 acre-feet. The total estimated ground-water discharge by evapotranspiration from Indian Wells Valley in 1953 was 8,000 acre-feet; this amount represents a decline from an estimated discharge of 11,000 acre-feet in 1912. The maximum developable yield (10,000 acre-feet) is judged to be less than the estimated 1912 ground-water discharge, because it is assumed that a continuing evapotranspiration loss of not less than 1,000 acre-feet per year would be required to maintain a hydraulic gradient toward the playa areas where the water quality is poor.”

St. Amand (1986) in *“Water Supply of Indian Wells Valley, California”* (prepared for NWC China Lake) states that (at page 1 [ES]):

“The total recharge to the system is estimated to be 11,000 acre-feet per year” and further that *“Before 1920 this same amount of water was lost by evapotranspiration from the China Lake playa.”*

This latter statement provides an important observation regarding the water budget of the IWV Basin—that is, that under current conditions groundwater pumping is recovering water that historically was largely lost to ET from the valley floor. St. Amand (1986) then goes on to state the following regarding safe yield:

“The safe perennial yield of the Indian Wells Valley is 10,000 acre-feet per year, provided that evapotranspiration in the playa area can be reduced to 1,000 acre-feet per year or less. If more water is used, it must come from the naturally stored underground water”.

With regard to groundwater storage, St. Amand (1986) states the following (also at page 1 [ES]) in recognition that of the available stored water only some is of suitable quality for most uses:

“About 2,200,000 acre-feet of useful water are stored in the basin. Of this, only about 600,000 acre-feet are available under the present pumping pattern before the aquifer is contaminated with saline water from the playa.”

On the basis of multiple data sources and hydrologic data from circa 1985, Bean (1989) estimated the recharge to the IWV Basin to be about 15,100 AFY (as also reported in DWR Bulletin 118). And in a 1996 study prepared by Houghton HGL for NAWS China Lake, recharge was reported to range from 11,000 AFY (citing St. Amand, 1986) to as high as 30,000 AFY (citing Thompson, 1929). The potential for recharge inter-basin flow in fractured rocks is also noted by Houghton HGL (1996; at page 1) who state that “Sources of recharge are believed to be from the surrounding mountains, Little Lake (located northwest of the Valley) and possibly fracture flow through the Sierra.”

The 2020 GSP (IWVGA, 2020) presents an estimate for the inflow (recharge) into the IWV Basin as 7,650 AFY. This estimate is based upon work performed by the Desert Research Institute (DRI) and is specific to the period 2011-2015 (IWVGA, 2020: citing McGraw et al, 2016; Garner et al, 2017). The GSP goes on to state that this rate of recharge (7,650 AFY) is also considered to be the current sustainable yield of the basin (IWVGA, 2020: at page ES-12). Inspection of **Figure 3-6** reveals that the period 2011-2015 was a dryer-than-average period in terms of precipitation on the bordering Sierras which—as I detail in **Section 4**—likely leads to these recharge and yield values being under-estimates of the longer-term averages for the basin.

Finally, the TWG undertook an evaluation of the safe yield of the IWV Basin which is detailed in their report “Assessment of Safe Yield for the Indian Wells Valley Groundwater Basin (TWG, 2024c). The TWG is a collection of groundwater professionals designated by parties representing more than 80% of the total groundwater production in water year (WY) 2022 from the IWV Basin. The TWG notes in their report that “This paper presents the TWG initial estimates of safe yield for the IWV Basin.” The TWG report also notes that (at page 6):

“The initial safe yield assessment is based entirely upon analyses of historical data and does not consider the potential effects of management (augmentation and mitigation) measures that might be applied under a physical solution to further maximize the amount of groundwater that might be safely and reasonably withdrawn.”

The TWG estimated safe yield using an empirical method based on groundwater storage changes in response to pumping across the IWV Basin. The analysis is based on data

available over the period 2014 through 2023. Using two calculation methods that only differ in certain assumptions, the TWG estimated the average safe yield for the period from 2014 through 2023 to range from about 14,300 AFY to 17,000 AFY and the TWG ultimately selected the lower value (14,300 AFY) as the most reliable of these estimates in part because of its reliance upon specific yield values derived from the Ramboll Model. Members of the TWG from Luhdorff & Scalmanini recently revisited their safe yield estimate using the same methods described previously by the TWG but using updated values for the specific yield which were derived from the Ramboll Model. The empirical method used by the TWG in their 2024 study, and by Luhdorff & Scalmanini in their 2025 study, does not *directly* account for potential discharges via ET processes—which could reduce the safe yield estimate—although some of the effects of ET may be implicit in the integration process used by the TWG. In my comparison of yield estimates provided in **Section 4** I consider the impact that accounting for ET may have on the yield estimates obtained by the TWG, and how accounting for ET brings my estimate and the TWG estimate closer together.

Estimates of the groundwater stored in the IWV Basin have varied widely in past studies. Two important factors leading to much of this variation are (a) the area and depth over which the calculations were made, and (b) the use of water quality criteria thresholds in the estimates. Some studies limit the area or the depth over which the storage is estimated—implying that beyond the prescribed area the aquifer is too thin, or beyond the prescribed depth the water quality is unsuitable for most uses—whereas other studies estimate the total quantity of stored water from the water table to the base of the aquifer as it is understood to lie at the time of the analysis.

Ramboll (2024) tabulates the results of, and details the methods used in, previous storage estimates by four groups spanning the period 1969 through 1993: those estimates range from 720,000 AF (for “usable” storage over a limited geographic area to a depth of only 100 feet) to 5.12 million acre-feet (MAF) (for total storage as reported by the California DWR in 1975). Ramboll (2024) then independently derived an estimate of total storage and also the storage containing lower total dissolved solids (TDS) in the IWV Basin, based on the 2019 HCF issued by Ramboll (2019) in conjunction with the Brackish Groundwater Resources Feasibility Study (Ramboll, 2019). In doing so, Ramboll (2024) obtained a range for the total storage of 89.2 MAF to 117.9 MAF and a range of 46.8 MAF to 62.3 MAF for groundwater exhibiting a TDS below 1,000 milligrams per liter (mg/L). As I note in **Section 4**, this storage estimate includes a deep hydrogeologic zone that contains water that may be of questionable quality, that I did not include in my estimate.

In their February 2024 assessment of groundwater storage, the IWV TWG estimated the total volume of groundwater in storage in the IWV Basin to be about 66.9 MAF, and the amount of fresh groundwater stored in the IWV Basin to be about 37.5 MAF (TWG, 2024b).

3.5 Conceptual Water Budget

The estimation of safe yield usually rests upon the development of a water budget for the basin. The complexity of the water budget depends upon the number of sources and sinks of water to and from the basin. Simple water budgets that assume a closed basin can be used if inter-basin flows are negligible. However, as noted above and by Thyne, et al (1999) in their *GSA Bulletin* contribution “*Evidence for inter-basin flow through bedrock in the southeastern Sierra Nevada*” inter-basin flow may occur via faulted and fractured bedrock. A system is usually considered balanced—that is, neither in chronic surplus nor in chronic overdraft—when there is no material change in storage.

Conceptualizing the IWV Basin as an “almost closed” basin with subsurface inflow from Rose Valley via Little Lake Gap and the possibility for subsurface outflow via fractured bedrock, a simple water budget (*absent pumping*) is presented below:

$$R_n = P - ET - (R_{off} - R_{on}) - (UF_{out} - UF_{in}) \quad (1)$$

Where:

- R_n = groundwater recharge
- P = natural precipitation
- ET = evapotranspiration (ET)
- R_{on} = run-on (overland flow) of surface water
- R_{off} = run-off (overland flow) of surface water
- UF_{in} = subsurface inter-basin inflow
- UF_{out} = subsurface inter-basin outflow

Natural precipitation (P) includes rainfall, snow, and fog, which in the IWV Basin is greater in the surrounding mountain areas than the valley floor. ET includes direct evaporation from soil and surface water bodies plus plant-mediated transpiration processes and is greater in the valley floor than in surrounding mountain areas. Run-off arises where precipitation is unable to infiltrate the subsurface—the resulting overland flow typically moves toward surface water bodies where it may later infiltrate as recharge. The net of the land surface processes infiltrates the soil and can become aquifer recharge, and the net of the subsurface interflows can lead to subsurface recharge.

In reality, the values of these water budget terms vary over time even under natural conditions, and as a result the quantities of water within the aquifer also change over time—i.e., there are changes in storage ($\Delta S \neq 0$) but these combination of periods of storage depletion and storage accrual balance over time.

When groundwater extraction via pumping is superimposed on the system, some of the water budget terms must change in order to accommodate this new withdrawal of water, and a more persistent change in aquifer storage can result from the pumping that cannot be neglected. This is shown below, where I have also included a term representing anthropogenic recharge via return flows and other sources:

$$\Delta S = [P - ET - (R_{\text{off}} - R_{\text{on}}) - (UF_{\text{out}} - UF_{\text{in}})] - Q_w + R_a \quad (2)$$

Where:

Q_w = pumping at wells

R_a = anthropogenic recharge

ΔS = change in storage

Figure 3-8 provides a simple schematic of the water budget represented by equation (2)—i.e., with pumping taking place, water levels declining, and storage declining.

Section 4.

Analysis of IWV Basin Safe Yield and Storage

This section provides an overview of the calculations that I made to estimate the safe yield and the stored water quantities for the IWV Basins. Because my calculations were based in part on the Ramboll Model, this section begins by describing the development of the Ramboll Model. Full details of the development and calibration of the Ramboll Model are provided by Ramboll (2025). What follows below is a synopsis of the main features and processes represented in the Ramboll Model. Because estimates of safe yield rest upon estimates of groundwater recharge and discharge, the greatest emphasis is placed in this section on estimated inflows to the system via surface and subsurface recharge (inter-basin inflows), followed by an assessment of the likely quantity of natural system outflows via ET.

4.1 Modeling Terms and Concepts

Some terms used in the environmental modeling community cause confusion when discussing the development and application of groundwater models. Some key terms are defined below for purposes of this report and the analyses that follow.

1. **Method** – a method is a specific approach taken to conceptualize and describe groundwater systems. Methods range from physical models—such as sand tanks—to mathematical models that use computer code. Mathematical methods include (i) analytical methods that simplify the groundwater system and do not require a “grid” for calculations, and (ii) numerical methods that represent subsurface conditions—such as different aquifers—by varying parameters throughout a 3D grid.²
2. **Code** – a sequence of procedures to implement the mathematical equations required by the chosen method. The MODFLOW-NWT code that was used to develop the Ramboll Model is an example of a numerical groundwater flow simulator. The BCM that

² Simplifying, a 3D model grid can be thought of as similar to a Rubik’s cube, in that each constituent cube has defined parameters. In a Rubik’s cube, those parameters are simple: the color of the cube’s faces. In a 3D model grid, the parameters attributed to each constituent cube can be numerous, including, e.g., vertical and horizontal hydraulic conductivity and storage properties. A 3D model grid simulates the flow of water between constituent cubes based on the laws of physics and these properties.

was used to estimate recharge rates for the Ramboll Model is an example of a numerical land surface process simulator.

3. **Model** – a set of prescribed inputs that collectively define the boundaries, properties, and sources and sinks (i.e., entry and exit points) of water for a specific study area. The Ramboll Model is an example of a site-specific groundwater flow model, and the statewide BCM is an example of a land surface model (LSM).
4. **Calibration** – The American Society for Testing and Materials (ASTM) defines calibration as the process of “*refining the model representation of the hydrogeologic framework, hydraulic properties, and boundary conditions to achieve a desired degree of correspondence between the model simulations and observations of the groundwater flow system*” (ASTM D5981/D5981M-18). The Ramboll Model was calibrated to historical groundwater level data, and I have compared outputs from the statewide BCM model to historical stream flows along the northern sierras.

4.2 Ramboll Model Design

4.2.1 Overview

The Ramboll Model is executed using the USGS MODFLOW-NWT simulation software (Version 1.3; Niswonger et al. 2011), and the construction of input files and review of model outputs is facilitated by the Groundwater Vistas (GWV) Graphical User Interface (GUI). MODFLOW-NWT—where NWT stands for *Newton Formulation*—is one of the recent releases of the public versions of the MODFLOW family of groundwater flow simulators developed by the USGS. MODFLOW-NWT simulates the movement of fresh groundwater and the exchange of water with surface water bodies such as streams, using a Newton-Raphson formulation to improve solution stability for unconfined (i.e., water table) groundwater-flow problems. The underlying code is in the public domain and is freely available from the USGS website.

4.2.2 Domain, Boundaries, and Layering

The geographic domain of the Ramboll Model is depicted in **Figure 4-1**, which also depicts the sub-watersheds that surround the IWV Basin from which the basin obtains most of its natural recharge via the MFR (MBR) processes detailed in **Section 3**. The model extent broadly follows the IWV Basin watershed topographical boundary. As a result, the furthest lateral extents of the Ramboll Model are defined as “no-flow” boundaries—meaning that the aquifer is assumed too thin to the point that there is negligible connection with adjacent basins. However, recharge to the IWV Basin via MFR processes is represented via

the MODFLOW-NWT Well (“WEL”) and Recharge (“RCH”) packages as detailed below, and inter-basin underflow from Rose Valley—is discussed below where recharge to the basin is described.

The Ramboll Model is a 3D model, which means that it represents the different layers of rock in the subsurface using different model layers. The Ramboll Model uses six (6) layers to represent the underlying aquifer units, with the first layer (layer 1) commencing at the land surface, and the layer number increasing with increasing depth in the basin. The six layers represent the uppermost three hydrogeologic zones (HGZs) such that model layers 1 and 2 represent HGZ1, model layers 3 and 4 represent HGZ2, and model layers 5 and 6 correspond to HGZ3. At its thickest point, the cumulative thickness of these units reaches nearly five thousand (5,000) feet. As noted in Section 3, the fourth HGZ—that is, HGZ4—is not represented in the Ramboll Model due to its comparatively low capacity to store and transmit water, and questionable water quality. This affects the quantity of water estimated to be stored within the IWV Basin aquifers, as I describe in **Section 4.4**.

4.2.3 Recharge

As detailed in **Section 3**, natural groundwater recharge to the IWV Basin arises mainly from MFR processes which are dominated by recharge and runoff from the Sierra Nevada and other surrounding mountain ranges, together with inter-basin flows from Rose Valley. These natural sources of recharge are at times supplemented by anthropogenic sources of recharge which include infiltration from irrigation returns and leaking water mains. **Figure 4-2** depicts the primary locations of groundwater recharge and discharge within the IWV Basin as represented in the Ramboll Model. Recharge to the Ramboll Model comprises three main categories: (1) natural recharge from precipitation, (2) natural recharge from underflow (inter-basin flows) and (3) recharge from anthropogenic sources.

With regard to recharge from natural sources: the dominance of MFR processes is common in semi-arid basins such as those encountered in Nevada and California. Technical methods and codes have been developed to estimate the quantity of recharge entering a basin from surrounding high ground. Most methods are based upon representing land surface processes that are important to the estimation of recharge rates, and the resulting models of these processes are commonly referred to as LSMs. The processes that LSMs represent include precipitation in the form of rainfall and snowfall; evaporation and plant-mediated transpiration (together, ET); overland flow or “run-off”; and infiltration through surface soils.

The BCM is a LSM that was originally developed for the Desert Southwest to evaluate hydrologic conditions in semi-arid basins (Flint et al., 2004; Flint and Flint, 2007). Although the BCM has seen many applications it was primarily developed by the USGS in cooperation with the DWR for application in California. The BCM is a grid-based model that calculates a water balance for a user-defined time step and spatial scale using climate inputs (“forces”)—principally precipitation and air temperature. The BCM uses the climate inputs to estimate potential evapotranspiration (ET_p or PET), accounts for snow accumulation and melt, calculates actual evapotranspiration (ET_a), and then estimates the quantity of excess water that becomes recharge or runoff. The BCM has gone through several phases of development culminating in BCM version 8 (BCMv8). BCMv8 outputs represent “unimpaired” stream flows and recharge—meaning they represent natural hydrologic conditions, where water is not extracted from nor delivered to a basin. Calculations for areas with mapped irrigated agriculture assume no irrigation, so that contributions from irrigation processes must be considered separately from the BCMv8 results (Flint et al., 2021).

The BCMv8 provides estimates of climate variables and outputs—including estimates of run-off and recharge—over the State of California on a two-dimensional (2D) grid with 270-meter (m) resolution. The BCMv8 was originally run on a monthly time scale to calculate the water balance for each 270 by 270-m (18-acre) grid cell statewide, including all basins draining into the State, for California WYs 1896–2019. To corroborate the BCMv8 outputs, the USGS compared simulation results to base-flow data from stream gages and to independent estimates of recharge (Flint et al., 2021). Time-series inputs required to execute the BCMv8 are comprised of gridded climate data primarily obtained from the PRISM group at OSU—where PRISM stands for “Parameter-elevation Regressions on Independent Slopes Model”. PRISM data have been made available by OSU for use in evaluating climate conditions since the mid-1990s.

The USGS also developed a BCM model of the IWW Basin, which is partially documented online at <https://www.usgs.gov/centers/california-water-science-center/science/using-basin-characterization-model-bcm-estimate>. This application of the BCM was based upon an earlier version of the BCM code dating from 2013—rather than the updated BCMv8 version released more recently by the USGS—and uses *actual* historical climate data only from 1981–2010, then calculating conditions from 2011 onward using *hypothetical* climate projections. The IWW Basin BCM is not fully documented, although a draft manuscript has been obtained that describes aspects of the model development (Saleh, et al. 2021); and

the publicly available outputs from the IWV Basin BCM only provide annual averages rather than the more frequent monthly values provided by the statewide BCMv8. For these reasons—the shorter time-period represented by the IWV Basin BCM model versus the statewide BCMv8; the use of the older code version; and lack of full documentation—the statewide BCMv8 rather than the IWV Basin BCM was used to provide estimates of natural recharge and run-off for input to the Ramboll Model to represent conditions through 2023.

The BCM is updated as new climate inputs become available. The BCMv8 statewide model was used to obtain water budgets—primarily, estimates of recharge and of runoff—for the following sub-watersheds that encompass the IWV Basin: Southern Sierra, Northern Sierra, Volcanics, Coso Range, Argus Range, El Paso, and Rose Valley (which was ultimately not used, as explained below). From the BCMv8 outputs, the calculated recharge rate was applied within defined cells in the Ramboll Model adjacent to each corresponding sub-watershed. USGS PP-1703-B (Flint and Flint, 2007) describes numerous studies of the proportion of the runoff that subsequently becomes groundwater recharge, noting that this percentage varies due to hydraulic properties of the soils and streambeds, and other factors. Because runoff is not routed—i.e., tracked from place to place—in the BCM model, the amount of runoff and its fate is treated as a basin characteristic (Flint and Flint, 2007). USGS PP-1703-B describes studies to estimate recharge and runoff for basins in the Basin and Range carbonate-aquifer system, indicating that about 15% of runoff becomes recharge (USGS PP-1703-B: also citing Lacznik et al., 2007; and Lundmark et al., 2007). Other studies in other areas suggest this percentage can range from about 10% to as high as 90% depending on the basin characteristics (USGS PP-1703-B). Ultimately, Flint and Flint (2007, USGS PP-1703-B) used 15% for their analyses, and Ramboll (2025) adopted the same fraction in their modeling. This fraction of the runoff calculated using BCMv8 was added to the model domain as a time-varying specified flux.

As part of my work, I compared the run-off that is calculated for the northern sierras using the statewide BCMv8 model with gaged stream flows obtained from three canyons that carry run-off from the sierras into the IWV Basin – Sand Canyon, Grapevine Canyon, and Nine Mile Canyon. **Figure 4-3** provides graphical comparisons of the BCMv8 calculated run-off and the summed stream flows within the three canyons for the period 1998 through 2023. Because Nine Mile Canyon has not been consistently gaged since the 1970's, the values for Nine Mile Canyon were estimated using a non-parametric (rank) regression method based on the available data record.

With regard to recharge via inter-basin flow: The BCMv8 statewide model computes runoff and groundwater recharge for the Rose Valley which is located north of and adjacent to the IWV Basin. Hydrologically, however, Rose Valley is not a sub-watershed that contributes recharge via the MFR processes represented by the BCM model; rather, Rose Valley contributes recharge to the IWV Basin via subsurface inter-basin underflows through Little Lake Gap. This subsurface interflow relationship between the basins is described or acknowledged in several publications including the GSP (IWVGA, 2020) and is the subject of ongoing studies to refine estimates of the quantities of interflow between basins. The quantities of underflow have been estimated using modeling and empirical calculations. The GSP (IWVGA, 2020) estimates the rate of recharge from Rose Valley to the IWV Basin at about 2,400 AFY (IWVGA, 2020 at Table 3-3) although as noted later in this report this estimate was developed for the period 2011 through 2015 which was a historically below-average period of precipitation and net recharge.

For the Ramboll Model, recharge rates from Rose Valley estimated using BCMv8 were not used—rather, a regression-based approach was used in its place. This employed an initial interflow estimated for the steady state period and then scaled this value for use in transient stress periods. For the steady state period, a value of 2,566 AFY underflow from Rose Valley was used in accordance with calculations detailed in the independent yield analysis undertaken by the TWG referred to as the Safe Yield White Paper. For the transient stress periods, variability in the rate of underflow was based upon variations in precipitation rates. This was accomplished by using the average rainfall for the period 1986–2023 as derived from the USGS BCM as a baseline, and then scaling this value for each year in the transient simulation period according to the ratio of precipitation that year to the long-term average value. This annual variation was then further refined to the quarterly stress periods of the Ramboll Model by using seasonal proportions of precipitation as follows: Q1 56%, Q2 8%, Q3 9%, and Q4 27% (Ramboll, 2025). The combined approach to representing Rose Valley underflows reflects both inter-annual and inter-seasonal variability.

Some studies identified a small amount of subsurface outflow from the IWV Basin to Salt Wells Valley as an inter-basin discharge (DRI, 2020). However, this outflow may occur from the shallow groundwater system near the playa and was not incorporated into the Ramboll Model (Ramboll, 2025), and I have not considered this outflow in my yield calculations.

With regard to recharge from other sources: There are five broad sources of anthropogenic recharge—water distribution system leakage, agricultural return flow, leakage from the LAA, periodic releases from the LAA and leakage from wastewater treatment. These are detailed by Ramboll (2025) in their discussion of sources of recharge represented in the Ramboll Model, together with the technical basis and assumptions underlying the estimated rates used for each of the five sources. Overall, as noted below in **Section 4.3**, from a basin-wide perspective these quantities of recharge are typically small compared to the natural recharge that results from mountain front processes as simulated using outputs from the BCMv8.

Comparison to other estimates: The combination of natural recharge rates estimated using the BCMv8, recharge via inter-basin flows, and anthropogenic recharge estimated using other methods, is listed on **Table 4-1** which tabulates on an annual basis the water budget terms obtained from the calibrated Ramboll Model. The green colored bars shown in the total recharge column illustrate in relative terms the quantity of total recharge each year. One reason for the difference in recharge rates—separate from the different methods used to obtain the estimates—between the Ramboll Model and the GSP (IWVGA, 2020) is that the GSP estimate of 7,650 AFY covers a timeframe (2011-2015) which can be seen from **Table 4-1** to be particularly dry compared to the longer period simulated using the BCMv8 and the Ramboll Model. This is also illustrated by the plot of estimated precipitation rates obtained from PRISM for the Northern Sierra as depicted in **Figure 3-6**. As a result, the recharge estimate provided in the GSP (2020) represents an under-estimate of the actual longer-term average recharge rate. The use of recharge estimates from this relatively dry period in safe yield calculations leads to underestimates for the reasonably anticipated longer-term average yields.

4.2.4 Evapotranspiration (ET)

At the core of the IWV Basin is an evaporative playa, which has long been recognized as a net discharge area for groundwater (see for example Lee, 1912; and St. Amand, 1986). Groundwater discharge in this area likely occurs as a combination of evaporation and transpiration from phreatophyte vegetation—that is, vegetation that draws its water from the underlying water table. Extending to the north and west of this playa area are channels that exhibit occasional and intermittent riparian vegetation—that is, vegetation that draws its water from the interface between land and streams (surface water).

As a potentially important process to the water budget of the IWW Basin, the Ramboll Model appropriately simulates the potential for this combination of ET processes to draw from groundwater using the MODFLOW-NWT Evapotranspiration (“ET”) Package. The upper panel of **Figure 4-4** depicts the general distribution of vegetation as contrasted with bare ground within the IWW Basin (**Figure 4-4a**), and the lower panel of **Figure 4-4** depicts and distinguishes the areas of the Ramboll Model where ET processes are simulated using the MODFLOW-NWT ET Package (**Figure 4-4b**). However, it is unclear whether these ET processes draw water from the *regional* aquifer to which my analysis of safe yield applies, and from which the overwhelming majority of groundwater pumping for beneficial uses occurs. This is because previous hydrogeological studies of the IWW Basin have indicated that the majority of the area over which ET processes occur lies above low permeability lacustrine clays within a “perched” shallow hydrogeologic zone (SHZ).

The most comprehensive of these studies is presented by TriEcoTt (2013), together with the base-wide hydrogeological characterization (BHC) of NAWS China Lake completed by Tetra Tech EM, Inc. (Tetra Tech 2002,2003). TriEcoTt (2013) prepared their report to support an application to remove the municipal and domestic (MUN) beneficial use designation for shallow groundwater within the SHZ in two broad geographic areas: (1) portions of the Salt Wells Valley (SWV) which lies to the south and southeast of the IWW Basin (i.e., outside the area of interest to this safe yield study), and (2) shallow groundwater within the IWW Basin (see also RWQCB, 2014). This application for de-designation was prepared of the U.S. Navy in regard to the NAWS China Lake facility which was established in 1943 and today covers about 1,735 square miles in three counties (Inyo, Kern, and San Bernardino), about 250 square miles of which lie within the IWW Basin (Ramboll, 2025).

With specific regard to the shallow groundwater within the IWW Basin, TriEcoTt (2013) indicated that the vertical boundary for the IWW Basin de-designation is defined by the top of the lacustrine clay sediments that separate the SHZ from the underlying intermediate hydrogeologic zone (IHZ). TriEcoTt (2013) describe the groundwater within the SHZ as arising from a combination of local recharge sources—including wastewater discharges—and that the SHZ groundwater ultimately discharges via springs, seeps, and ET. TriEcoTt (2013) also state that under present-day conditions the only wells open to the SHZ are monitoring wells associated with environmental investigations, and that due to poor water quality and lack of hydraulic connection with the IHZ, groundwater in the SHZ is unlikely to be used for future MUN purposes. The technical justification provided by TriEcoTt (2013) is based in part upon the BHC (Tetra Tech 2002,2003) which describes three (3) primary water

bearing zones – shallow (SHZ), intermediate (IHZ), and deep (DHZ) – and indicates that although under present-day conditions higher elevation heads are found in the SHZ than the IHZ, vertical (downward) flow is limited in most places by the presence of a lacustrine clay. TriEcoTt (2013) state that while the IWV Basin encompasses about 382,000 acres the de-designation only applies to about 20% of this area, as shown in **Figure 4-5** which depicts the area delineated for de-designation.

Given the foregoing, it is likely that the majority of ET demand—that is, the discharge of groundwater via ET processes—that is simulated by the Ramboll Model takes place within this SHZ and does not draw water from the regional aquifer. In this conceptual model the ET demand is met by a combination of local precipitation, anthropogenic water sources including wastewater discharges, and occasional run-off. For this reason, as described in this report, the safe yield number that I consider most reliable does not include material losses via ET. However, to ensure robust management of the IWV Basins resources I have also provided a safe yield number that includes the effects of ET processes so that this possibility is not entirely neglected.

4.2.5 Groundwater Pumping

Pumping in the Ramboll Model is represented using the MODFLOW-NWT Well (“WEL”) Package and is based upon a multi-year compilation of historical pumping rates from numerous users of basin resources (Ramboll, 2025). The GSP (IWVGA, 2020) and the report of the Ramboll Model (Ramboll, 2025), among other documents and reports, provide detailed discussions of groundwater pumping within the IWV Basin. Although there are some uncertainties regarding specific pumping rates for some water users, the broad patterns and quantities of pumping appear to be comparable between the compilation by Ramboll (2025) and the GSP (IWVGA, 2020) as depicted in **Figure 3-7**.

4.2.6 Aquifer Properties, Parameterization, and Calibration

Parameters are assigned to the cells of the Ramboll Model to represent the properties of water transmission and storage: those parameters are the hydraulic conductivity (horizontal and vertical) and the storativity of the sediments. The storativity includes two different mechanisms by which water is released from the aquifer:

- First, specific yield, is the volume of water that “drains” from the pore space under pumping. This is often referred to as the “unconfined storage”—because the water table falls and the unsaturated zone above the water table increases in thickness.

- Second, specific storage, is the volume of water released due to pressure changes in the aquifer. This is often referred to as “confined storage”—because the aquifer does not “dry up” under pumping, rather the rate of water released under pumping relates to both the compressibility of the aquifer and the water.

Ramboll (2025) used a combination of geologic or stratigraphic mapping and sediment texture analysis to assign initial values of the hydraulic conductivity and storage parameters in the model. These initial parameter values were then updated via calibration of modeled water levels at the location of wells in the basin to the values measured historically at those wells (Ramboll, 2025). The calibration was undertaken using a combination of manual adjustments to parameters together with the use of automated parameter estimation techniques facilitated through the use of the parameter estimation software (PEST), which is used for model independent parameter estimation and uncertainty analysis (Doherty, 2010). The Ramboll modeling report (Ramboll, 2025) details the calibration process and results. **Figure 4-6** presents an example image of the distribution of horizontal hydraulic conductivity within the uppermost layer (layer 1) of the Ramboll Model as derived through a combination of sediment textural analysis and calibration to historical water level measurements. I reviewed the model calibration process that Ramboll used with their model, including their use of sediment texture data and geophysical data including AEM data obtained through the DWR-led surveys, and found that the calibration qualitatively corroborates the yield estimates that I present in the following section.

4.3 Yield Calculations

I have used the Ramboll Model to calculate the likely safe yield of the IWV Basin as the average rate of groundwater recharge which is dominated by natural recharge calculated using the statewide BCMv8 model. I performed my calculations using the USGS ZoneBudget (Harbaugh, 2009) utility that reads the outputs from a MODFLOW-NWT simulation and computes the rates of inflow, outflow, pumping, and change in storage for processing and plotting purposes. My annual summary of the outputs obtained when using ZoneBudget together with the Ramboll Model is listed on **Table 4-1**.

On this basis, I estimate the total safe yield to be 14,375 AFY (**Table 4-2**). This estimate does not include the average rate of groundwater discharge via ET that is calculated using the Ramboll Model. As detailed above, there is some uncertainty regarding whether ET processes in the valley floor draw water from the regional aquifer to which my estimate of

safe yield applies or from an upper, isolated, shallow aquifer. Because I recognize that there is uncertainty regarding the demand that ET makes on the regional groundwater system, I also provide a lower estimate for the yield that includes ET which is 12,329 AFY. These values are listed on **Table 4-2** which provides the results of my yield calculations highlighted in green based on the Ramboll Model and statewide BCMv8 model averaged over the period 1980 through 2023.

My estimate compares quite well with the estimate provided by the TWG in their September 2024 assessment of safe yield (14,300 AFY to 17,000 AFY with the lower value preferred) (TWG, 2024c). My estimate is larger than the value of 7,650 AFY reported in the GSP (IWVGA, 2020). Setting aside for the moment the methodological differences in the analyses completed by the TWG and by the IWVGA, I believe an important reason for the difference in the yield estimates is the different time periods used to obtain the estimates, as described below:

- **GSP sustainable yield estimate of 7,650 AFY.** This estimate is likely an underestimate of the reasonably anticipated longer-term average yield of the IWV Basin because the GSP estimate is based upon a period (2011-2015) that is particularly dry compared to the longer available record simulated using the BCMv8 and the Ramboll Model. This is illustrated by the plot of estimated precipitation rates obtained from PRISM for the Northern Sierra (**Figure 3-6**), and by inspection of the recharge plotted on **Figure 4-5** and listed on **Table 4-1**.
- **TWG higher-end estimate of 17,000 AFY.** The higher-end estimate obtained by the TWG may overestimate the reasonably anticipated longer-term average yield of the IWV Basin because the TWG estimate is based upon a period (2014-2023) that is fairly wet compared to the longer available record simulated using the BCMv8 and the Ramboll Model. This is illustrated by the plot of estimated precipitation rates obtained from PRISM for the Northern Sierra (**Figure 3-6**), and by inspection of the recharge plotted on **Figure 4-7** and listed on **Table 4-1**.

To support my interpretation that the period considered for yield calculations can materially affect the estimates obtained, I have listed “hypothetical” yield values on **Table 4-2** as obtained using the same method I used for my estimates (averaged over the period 1980 through 2023) but averaged over two other periods: first, 2011-2015, the periods considered in the GSP; and second, 2014-2023, the period considered by the TWG. Inspection of **Table 4-2** shows that using dry periods to estimate yields—such as 2011-

2015—results in low estimates for the safe yield and using wetter-than-average periods—such as 2014-2023—can lead to higher-than-average estimates. This comparison suggests that the Ramboll Model provides consistent and reliable safe yield estimates.

As an additional test of whether my yield estimates are consistent and reliable, I worked with my colleague Vivek Bedekar PhD to make one additional calculation using the Ramboll Model. Dutcher and Moyle, Jr. (1973) and St. Amand (1986) among others recognized that the discharge rate attributable to ET was much higher in the past than it is under present-day conditions. Dutcher and Moyle, Jr. (1973) stated “*The total estimated ground-water discharge by evapotranspiration from Indian Wells Valley in 1953 was 8,000 acre-feet; this amount represents a decline from an estimated discharge of 11,000 acre-feet in 1912.*” and St. Amand (1986) stated that “*The total recharge to the system is estimated to be 11,000 acre-feet per year*” and further that “*Before 1920 this same amount of water was lost by evapotranspiration from the China Lake playa.*” To test this assumption, we used the Ramboll Model to make a “No-Pumping” simulation with the intent of identifying the calculated change in ET to see if it is indeed consistent with historical information. To accomplish this, the Ramboll Model was executed with all inputs unchanged except groundwater pumping was excluded from the simulation. Review of the standard MODFLOW-NWT output file identified that the average change in the discharge rate via ET and surface drains over the simulation period was about 16,000 AFY, which is larger than but broadly consistent with the statements made by Dutcher and Moyle, Jr. (1973) and St. Amand (1986) and further corroborates the conceptual model of the IWV Basin and my yield estimates.

I recognize that although the vast majority of recharge that the IWV Basin receives is from natural MFR/MBR processes, there is a contribution to groundwater recharge from non-natural or non-native sources. I have estimated the native and non-native fractions of this recharge to apply to my safe yield estimate. To do this, I derived an estimate of the percentage of the total recharge that could be reasonably described as arising from non-native sources. The resulting proportions are listed as annual values on **Table 4-3**—which lists the total recharge and the native / non-native fractions for the Ramboll Model simulated period of 1980-2023—and depicted on a stacked bar plot in **Figure 4-7**. As shown on **Table 4-3**, the native proportion likely constitutes over 90% of the total recharge.

4.4 Storage Calculation

Because the Ramboll Model constitutes the most current 3D numerical representation of the HCM as described by Ramboll (2019)—including interpretation of deep aquifer characterization boreholes, seismic and electro-magnetic geophysical data, and other information—my estimate of the groundwater that is stored in the IWV Basin is based upon calculations made using the Ramboll Model (2025). I made these calculations together with my colleague Vivek Bedekar PhD during our review and execution of the Ramboll Model.

The storage calculations rest upon three primary inputs: (1) the 3D numerical grid that defines the geographic extents and the depth of the IWV Basin aquifer system, (2) the groundwater elevations simulated by the model, and (3) the parameters used in the model to represent the storage properties of the IWV Basin aquifers. As noted earlier in **Section 4**, the geographic domain of the model aligns with the watershed of the IWV Basin. The calculations were made as follows: first, the groundwater level simulated by the model within each of the 3D model cells provides a value for the saturated thickness—i.e., the thickness of the water-bearing zone—in each model cell. Three possible cases must be considered when calculating the thickness of the water-bearing zone in each cell:

1. If the water level lies within the cell—in which case the cell is “unconfined”—then the difference between the water level and the base of the cell is used as the thickness.
2. If the water level is higher than the top of the cell—in which case the cell is considered to be storing water under pressure—then the cell thickness is used as the saturated thickness.
3. If the water level is less than or equal to the bottom elevation of the cell—in which case the cell is essentially “dry”—then the saturated thickness is assumed to be zero (there is no water in that cell).

In each case, the volume of water is obtained by multiplying the saturated cell thickness by the cell area and the specific yield for every model grid cell. The total volume of water aggregated over all active model cells that have a non-zero saturated thickness therefore provides the total volume of stored water. Confined storage—i.e., the water that is stored under pressure as described in **Section 3** and distinguished from drainable storage—was not considered in the volume calculations.

Using this approach, I estimate the total volume of groundwater in storage to be about 51 MAF. My estimate compares quite well with the average estimate for total storage of 66.9 MAF provided by the TWG in their February 2024 assessment of groundwater storage for HGZ1, HGZ2 and HGZ3 combined (TWG, 2024b at Table 15). My estimate is less than that obtained by Ramboll (2024) who provided a range for total storage of 85.1 to 115.6 MAF including HGZ4, and a range of 57.5 MAF to 69.5 MAF for the combination of HGZ1, HGZ2 and HGZ3 (i.e., not including HGZ4) (Ramboll, 2024 at Table 8). My storage estimate is larger than the historical storage estimates that I listed in **Section 3** which ranged from 720,000 AF for “usable” storage to 5.12 MAF for total storage—however, as I detailed in **Section 3** those estimates were for limited geographical and vertical extents of the basin whereas my estimate was derived for the entire IWV Basin (excluding HGZ4 which contains water of questionable quality within very deep geologic deposits that may not easily yield stored water).

The estimate I provide for total storage does not explicitly consider the quality of the groundwater—in terms of the TDS—in the calculations, so that the resulting estimate of stored volume represents all water present in the IWV Basin regardless of quality. However, I recognize that not all of this water is of potable quality, and that the volume of water that is of potable quality will be substantially less.

It is important to recognize that in calculating and offering an opinion on the total volume of groundwater stored in the IWV Basin, I do not imply that this water can be recovered inexorably as this would constitute groundwater mining and would put the basin in a state of persistent overdraft. However, recognition of the presence of a substantial volume of water in storage is important to the future management of the basin. Given the historically variable precipitation and recharge rates that the IWV Basin has experienced—and the many years that it can take for this high variability to converge on longer-term average rates (as depicted on **Figure 3-6**)—it is likely that the timeline for implementation of SGMA requirements will also experience such multi-year periods of below average recharge and concomitant storage depletion followed by periods of excess and replenishment.

Section 5. Recommendations

Although substantial data have been obtained to characterize the IWV Basin, and the Ramboll Model represents the culmination of a great effort to develop a tool for water resource management, improvements can be made to the knowledge and understanding of the basin that—when incorporated into regular updates to the Ramboll Model—would further improve understanding and also the predictive capability of the model. The IWV Basin exhibits highly variable climatic conditions leading to widely different recharge rates year-over-year. This variability leads to extended dry periods and widely varying estimates of safe yield when those estimates are based on relatively short periods of time—e.g., less than about 10 to 15 years. Groundwater users in the IWV Basin can anticipate periods of quite prolonged dry spells—leading to storage depletion—during the future implementation period for meeting SGMA requirements, followed by opportunities for storage accrual during wetter periods. Future basin management decisions should be based upon the best available science, data, methods, and models in anticipation of this variability. The following recommendations are offered to help improve understanding of the IWV Basin hydrogeologic conditions—in particular, the locations and rates of natural recharge and groundwater discharge—for water resource management purposes:

- Additional gaging of mountain-front streams.
- Further characterization of inter-basin under-flows from Rose Valley / Little Lake.
- Infiltration studies to improve understanding of the proportion of run-off that recharges the IWV Basin under natural conditions, and opportunities for enhancement of this recharge.
- Installation of shallow monitoring wells near the IWV Basin margins to improve understanding of the aquifer response to recharge events.
- Targeted aquifer testing to refine estimates of hydraulic parameters.
- Further analysis of ET processes and rates at the local and basin-wide scale.

Section 6.

References

ASTM D5981/D5981M-18. 2018. Standard Guide for Calibrating a Groundwater Flow Model Application

Bean, R.T. 1989. Hydrogeologic Conditions in Indian Wells Valley and Vicinity. February.

Berenbrock, C., and P. Martin. 1991. *The Ground-Water Flow System in Indian Wells Valley, Kern, Inyo, and San Bernardino Counties, California*. U.S. Geological Survey. Water-Resources Investigations Report 89-4191.

California Department of Water Resources (DWR). 2004. California's Groundwater Bulletin 118. February 27.

California Department of Water Resources (DWR). 2016. California's Groundwater Bulletin 118 Interim Update. December 22.

California Department of Water Resources (DWR). 2020a. California's Groundwater—Update 2020: Sacramento, Calif., DWR Bulletin 118, 485 p.

California Department of Water Resources (DWR). 2020b. AEM Factsheet - California Department of Water Resources. Available at <https://water.ca.gov/-/media/DWR-Website/Web-Pages/Programs/Groundwater-Management/Data-and-Tools/Files/Prop68/P1-2020-AEM-Fact-Sheet.pdf>

California Department of Water Resources. 2022. Letter from Paul Gosselin to Don Zdeba, Indian Wells Valley Groundwater Authority GSA, Regarding: "Approved" Determination of the 2020 Indian Wells Valley Basin Groundwater Sustainability Plan. January 13.

California Regional Water Quality Control Board (RWQCB). 2014. Staff Report and Substitute Environmental Document, Proposed Amendments to the Water Quality Control Plan for the Lahontan Region - Removal of the Municipal and Domestic Supply (MUN) Beneficial Use Designation from Ground Waters of Naval Air Weapons Station China Lake, Kern, Inyo, and San Bernardino Counties. Draft. November 26.

Supreme Court of California. 1975. *City of Los Angeles v. City of San Fernando*. 14 Cal.3d 199.

Desert Research Institute (DRI). 2017. Technical Memorandum from Chris Garner, Steve Bacon, Greg Pohll, and Jenny Chapman to Jean Moran, Stetson Engineers, Regarding: Indian Wells Valley Groundwater Model Update. November 17.

Desert Research Institute (DRI). 2020. Isotopic Evaluation of Groundwater Recharge and Flow in Indian Wells Valley. Publication No. 41281. December.

Doherty, J. (2010) PEST, Model-Independent Parameter Estimation—User Manual. 5th Edition, with Slight Additions, Watermark Numerical Computing, Brisbane.

Dutcher, L.C., and W.R. Moyle, Jr. 1973. *Geologic and Hydrologic Features of Indian Wells Valley, California*. U.S. Geological Survey. Water-Supply Paper 2007.

Erskine, M.C. 1989. Review of the Geohydrology of the Indian Wells Valley Region, Kern, Inyo, and San Bernardino Counties, California. June 29.

Flint, A.L., L.E. Flint, J.A. Hevesi, and J.B. Blainey. 2004. Fundamental Concepts of Recharge in the Desert Southwest: A Regional Modeling Perspective. In *Groundwater Recharge in a Desert Environment: The Southwestern United States*. Hogan, J.F., Phillips, F.M., and Scanlon, B.R. eds. Vol. 9. 159-184.

Flint, L.E., and A.L. Flint. 2007. Regional Analysis of Ground-Water Recharge. US Geological Survey Professional Paper 1703-B.

Flint, L.E., A.L. Flint, and M.A. Stern. 2021. *The Basin Characterization Model-A Regional Water Balance Software Package*. U.S. Geological Survey. Techniques and Methods 6-H1.

Harbaugh, A.W. 1990. *A Computer Program for Calculating Subregional Water Budgets Using Results from the U.S. Geological Survey Modular Three-dimensional Finite-difference Ground-water Flow Model*. U.S. Geological Survey. Open-File Report 90-392.

Harbaugh, A. W., 2009, Zonebudget Version 3.01, A computer program for computing subregional water budgets for MODFLOW ground-water flow models, U.S. Geological Survey Groundwater Software., available for download from water.usgs.gov/nrp/gwsoftware/zonebud3/zonebudget3.html

Houghton HydroGeo-Logic. 1996. Geohydrologic Investigation Report, Naval Air Weapons Station, Indian Wells Valley, China Lake, California. November 30.

Indian Wells Valley Groundwater Authority (IWVGA). 2020. Groundwater Sustainability Plan for the Indian Wells Valley Groundwater Basin, Bulletin 118, Basin No. 6-054, Indian Wells Valley Groundwater Authority. January.

Indian Wells Valley Groundwater Authority (IWVGA). 2025. 2025 Periodic Evaluation, Indian Wells Valley Groundwater Basin Groundwater Sustainability Plan, Bulletin 118, Basin No. 6-054. March.

Indian Wells Valley Technical Working Group (TWG). 2024a. Appendix A - Technical Working Group: Evaluation of Previous Estimates of Safe Yield and Similar Studies for the Indian Wells Valley Groundwater Basin. September 11.

Indian Wells Valley Technical Working Group (TWG). 2024b. Assessment of Groundwater Storage for the Indian Wells Valley Groundwater Basin. February 23.

Indian Wells Valley Technical Working Group (TWG). 2024c. Assessment of Safe Yield for the Indian Wells Valley Groundwater Basin. September 4.

Laczniak, R.J., Flint, A.L., Moreo, M.T., Kochenmus, L.A., Lundmark, K.W., Pohll, Greg, Carroll, R.W.H., Smith, J.L., Welbron, T.L., Heilweil, V.M., and Pavelko, M.T., 2007, Groundwater budgets, in Welch, A.H., and Bright, D.J., eds., Water resources of the Basin and Range carbonate-rock aquifer system in White Pine County, Nevada, and adjacent areas in Nevada and Utah—draft report: U.S. Geological Survey Open-File Report 2007-1156, p. 49-89. [Note: this report was superseded by *Scientific Investigations Report 2007-5261*].

Lee, C.H. 1912. *Ground Water Resources of Indian Wells Valley California*. California State Conservation Commission in co-operation with the United States Geological Survey.

Markovich, K.H., A.H. Manning, L.E. Condon, and Jennifer C. McIntosh. 2019. Mountain-Block Recharge: A Review of Current Understanding: *Water Resources Research* 55, no. 11: 8278-8304.

McGraw, D., R. Carroll, G. Pohll, J. Chapman, S. Bacon, and R. Jasoni. 2016. Groundwater Resource Sustainability: Modeling Evaluation for the Naval Air Weapons Station, China Lake, California. NAWCWD TP 8811. September.

Monastero, F.C., Walker, J.D., Katzenstein, A.M. and A.E. Sabin. 2002. Neogene evolution of the Indian Wells Valley, east-central California, in Glazner, A.F., Walker, J.D., and J.M. Bartley, eds.; *Geologic Evolution of the Mojave Desert and Southwestern Basin and Range*: Boulder, Colorado, Geological Society of America Memoir 195, p. 199-228.

Niswonger RG, Panday S, Ibaraki M. 2011. MODFLOW-NWT, A Newton formulation for MODFLOW-2005: USGS Survey Techniques and Methods 6–A37

Ramboll. 2019. Hydrogeologic Conceptual Framework Indian Wells Valley. June.

Ramboll. 2024. Storage Estimate Indian Wells Valley. Originally issue September 2022, Revised June 2023 and February 2024.

Ramboll. 2025. Indian Wells Valley Groundwater Flow Model, Indian Wells Valley Basin, California. August.

Ribble, G.E. 2000. A Methodology for Estimating Water Yield of Sierra Watersheds Tributary to Indian Wells Valley. February.

Rosenthal, J.S., Meyer, J., Palacios-Fest, M.R., Young, D.C., Ugan, A., Byrd, B.F., Gobalet, K., Giacomo, J., 2017. Paleohydrology of China Lake basin and the context of early human occupation in the northwestern Mojave Desert, USA. *Quat. Sci. Rev.* 167, 112–139.

Saleh, D., L. Flint, and M. Stern. 2021. Assessing Natural Recharge in Indian Wells Valley, California: A Basin Characterization Model Case Study.

Smith, R.T. 2024. SGMA Gone Awry in Indian Wells Valley. April 9.

St.-Amand, P. 1986. Water Supply of Indian Wells Valley, California. NWC TP 6404. April.

Stonestrom, D.A., J. Constantz, T.P.A. Ferré, and S.A. Leake, eds. 2007. *Ground-Water Recharge in the Arid and Semiarid Southwestern United States*. U.S. Geological Survey. Professional Paper 1703.

Tetra Tech EM Inc. 2003. Basewide Hydrogeologic Characterization Summary Report, Naval Air Weapons Station, China Lake, California. Final. July 31.

Thompson, D.G. 1929. The Mojave Desert Region, California. USGS Water-Supply Paper 578. pp. 144-85.

Thyne, G.D., J.M. Gillespie, and J.R. Ostdick. 1999. Evidence for Interbasin Flow through Bedrock in the Southeastern Sierra Nevada: *GSA Bulletin* 111: 1600-1616.

TriEcoTt. 2013. Technical Justification for Beneficial Use Changes for Groundwater in Salt Wells Valley and Shallow Groundwater in Eastern Indian Wells Valley, Naval Air Weapons Station, China Lake, California. Final. February 12.

U.S. Bureau of Reclamation. 1992. *Indian Wells Valley Groundwater Project, Volume II, Technical Report*. December.

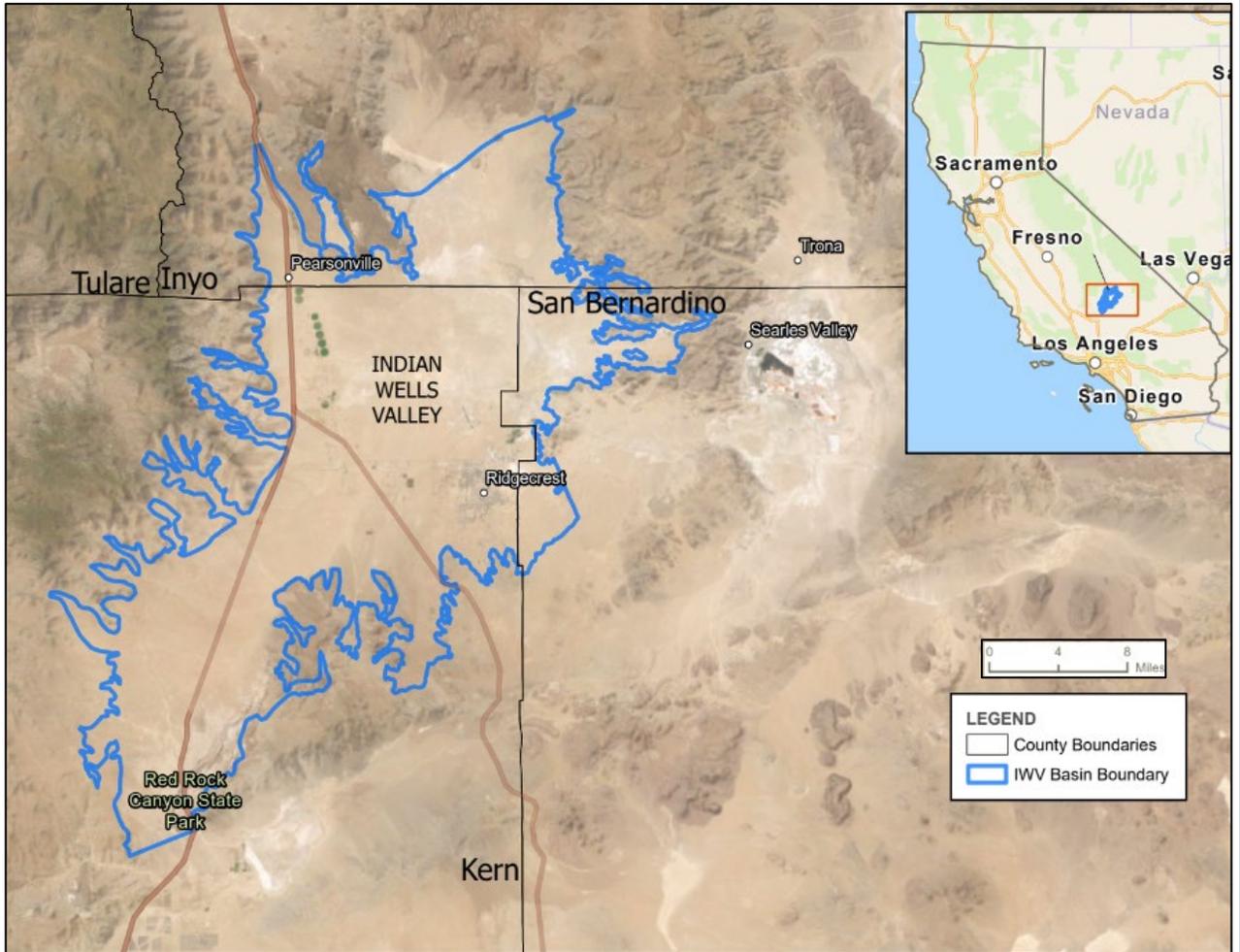
Warner, J.W. 1975. Ground-water quality in Indian Wells Valley, California. U.S. Geological Survey Water-Resources Investigations Report (WRI) 75-8. Prepared in cooperation with the Department of the Navy and the Indian Wells Valley County Water District.

<https://doi.org/10.3133/wri758>.

Williams, D.V. 2004. Hydrogeologic and Hydrochemical Framework of Indian Wells Valley, California: Evidence for Interbasin Flow in the Southern Sierra Nevada. Colorado School of Mines. June 24.

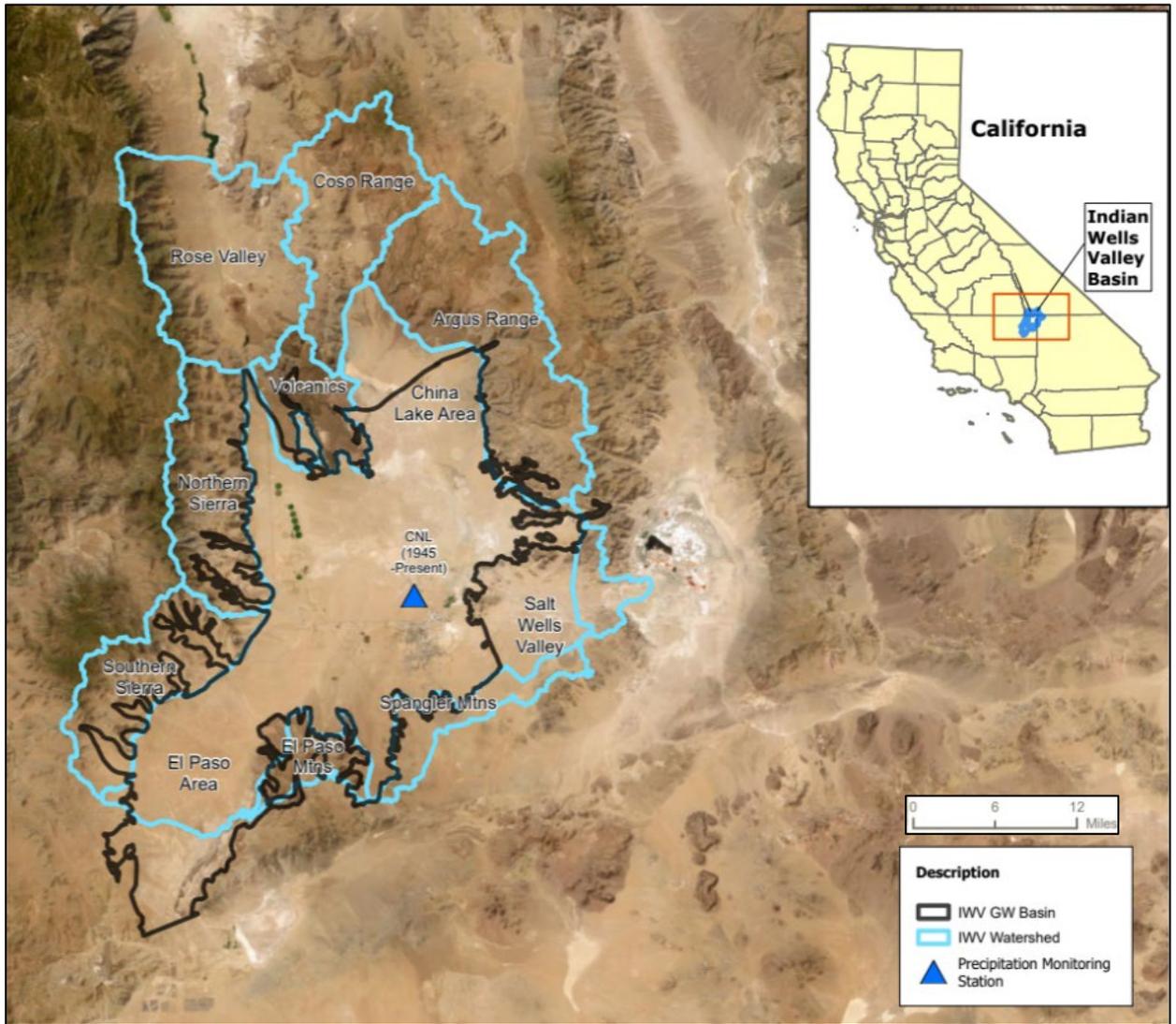
**FIGURES
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FIGURES



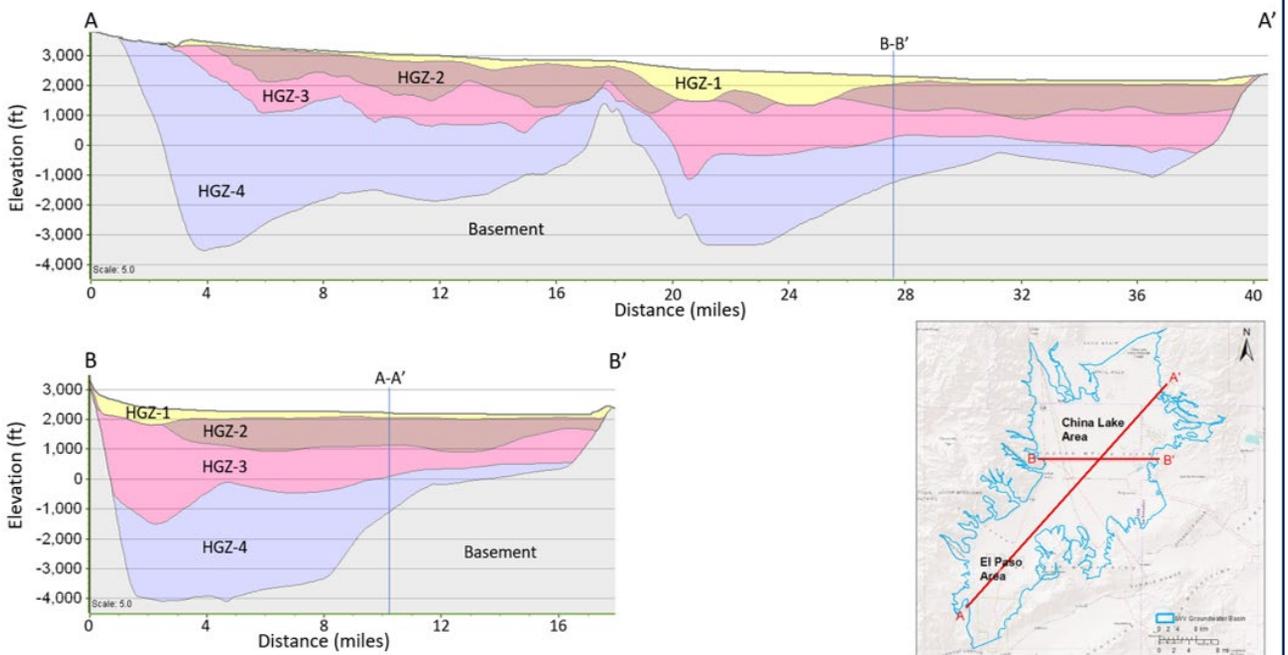
SOURCE(S):
 Modified after Ramboll (2025)

Figure 3-1: General Study Area



SOURCE(S):
Modified after Ramboll (2025)

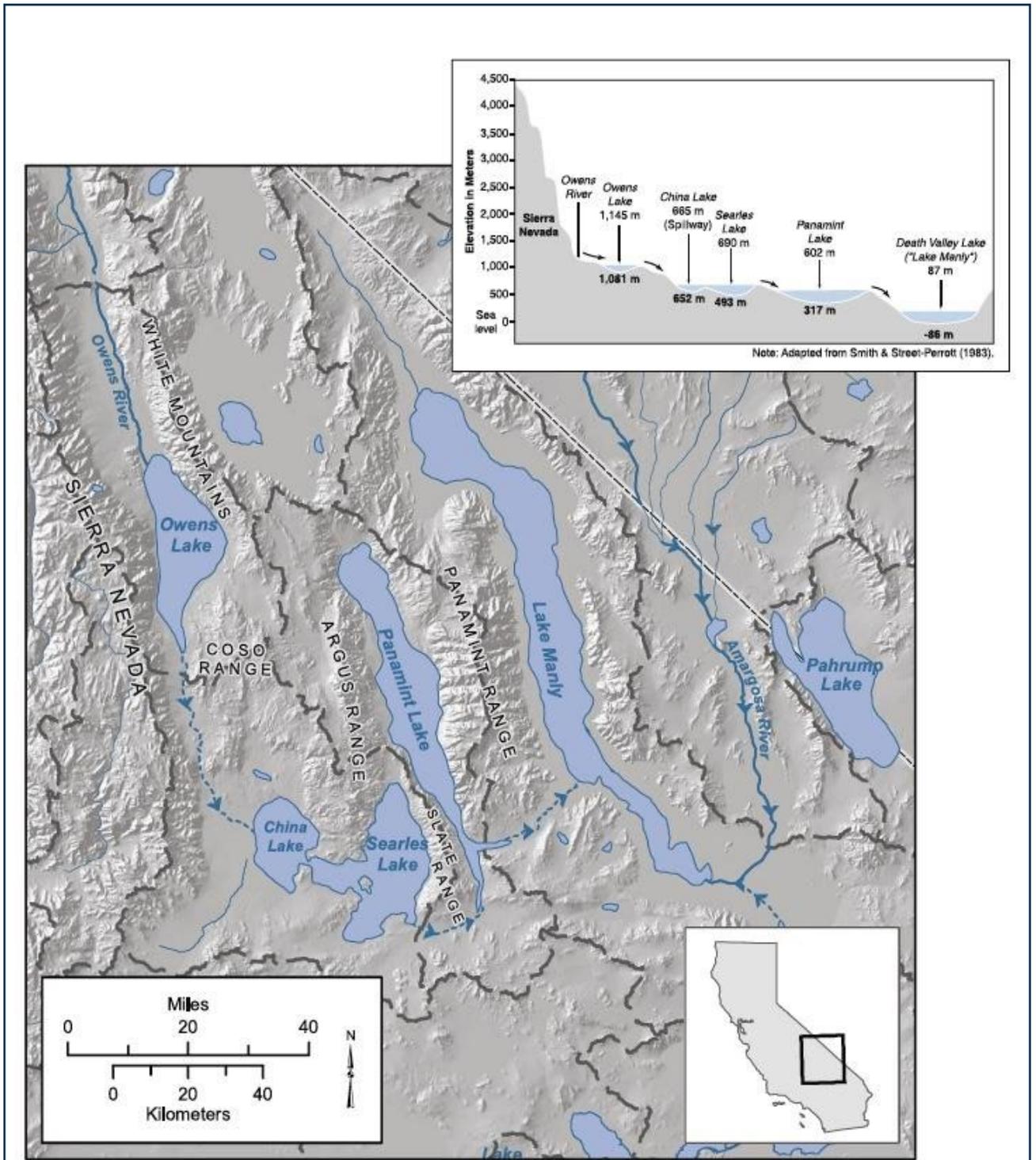
Figure 3-2: IWV Basin and Surrounding Ranges **IWVWD 000006265**



NOTE:
 HGZ-1,-2,-3 are included in the Ramboll Model
 HGZ-4 is not included due to low productivity
 SOURCE(S):
 Modified after Ramboll (2025)

IWVWD 000006266

Figure 3-3: Geologic Cross Section(s) (After Ramboll, 2025)



SOURCE(S):
 After Ramboll (2025) and Rosenthal et al, (2017)

IWVWD 000006267

Figure 3-4: Ancestral Owens River and inter-Basin Connections (after Rosenthal et al., 2017)

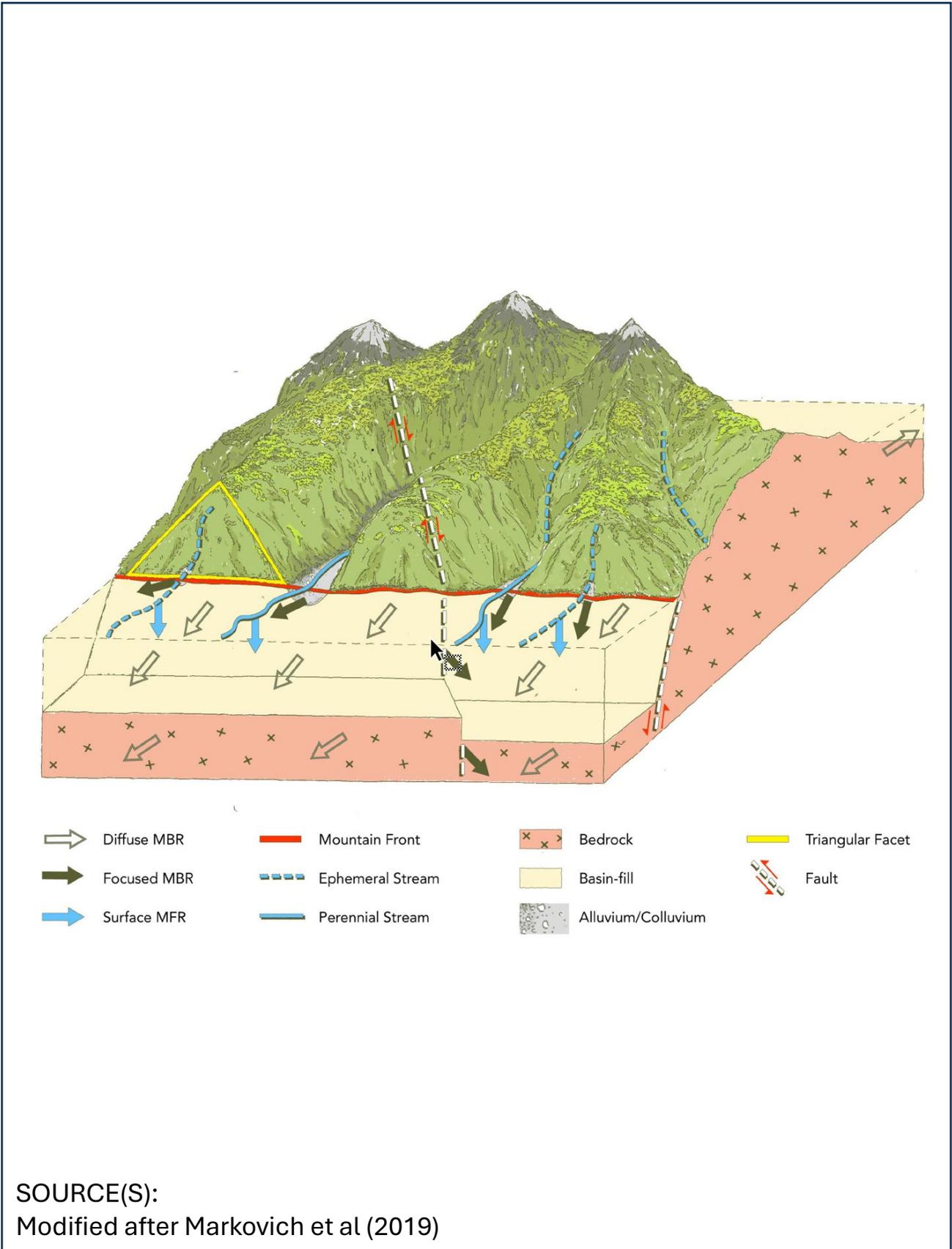
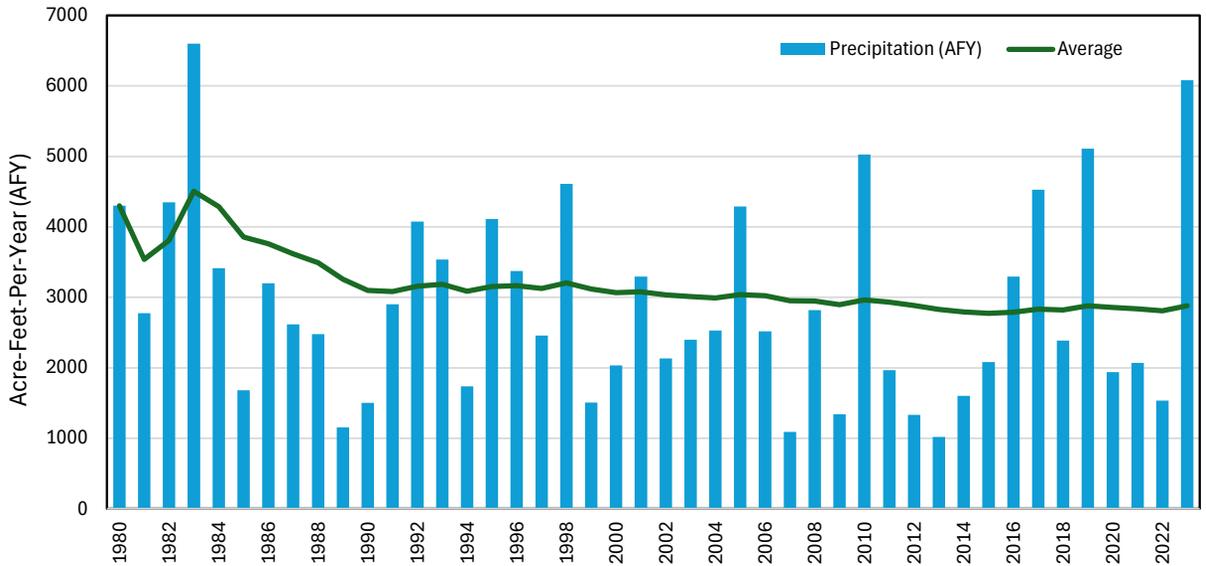
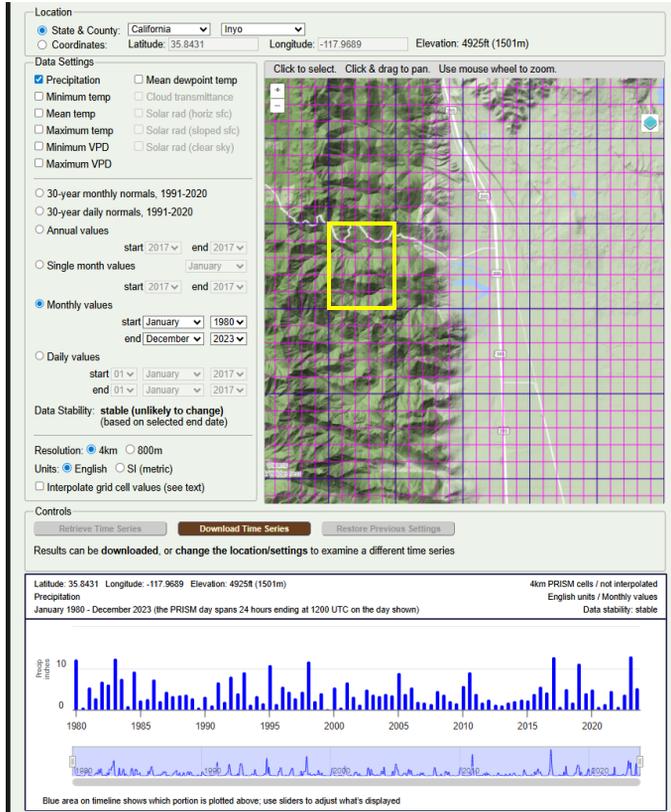


Figure 3-5: Schematic of Mountain Front Recharge (MFR) Processes (after Markovich et al, 2019)



SOURCE(S):
 PRISM Group at Oregon State University
<https://prism.oregonstate.edu/explorer/>

IWVWD 000006269

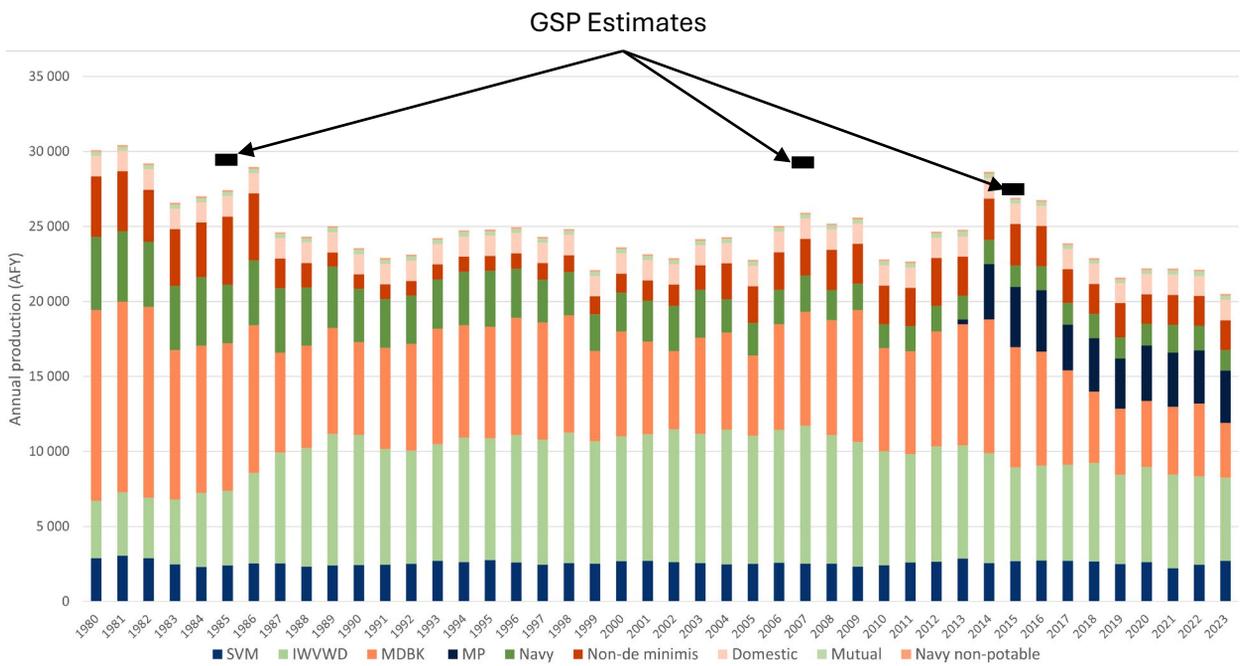
Figure 3-6: Historical Precipitation (derived from PRISM)

Table 3-1 Historical Pumping Distribution by Water Use (Calendar Year)

Water Use	1975	1985	2007	2015
	15,980 AF	29,730	29,433 AF	25,285 AF
Agriculture, Irrigation	22%	48%	42%	52%
Industrial	17%	8%	9%	10%
Municipal/Domestic ²	29%	31%	41%	33%
U.S. Navy	31%	9%	9%	6%

Note: individual percentages have been rounded to the nearest 1%, and the sum of the numbers may not equal 100% due to this summation rounding error.

1. Agriculture, Irrigation includes Meadowbrook Farms, Simons Ranch, City of Ridgecrest, Neal Ranch, Quist Farms, S. Leroy, and other Orchards estimated on the Cooperative Group's Pumping Table included in Appendix 3-A.
2. City/Municipal/Domestic includes China Lake Acres, IWVWD, Inyokern CSD, Private Wells and R/C Heights estimated on the Cooperative Group's Pumping Table included in Appendix 3-A

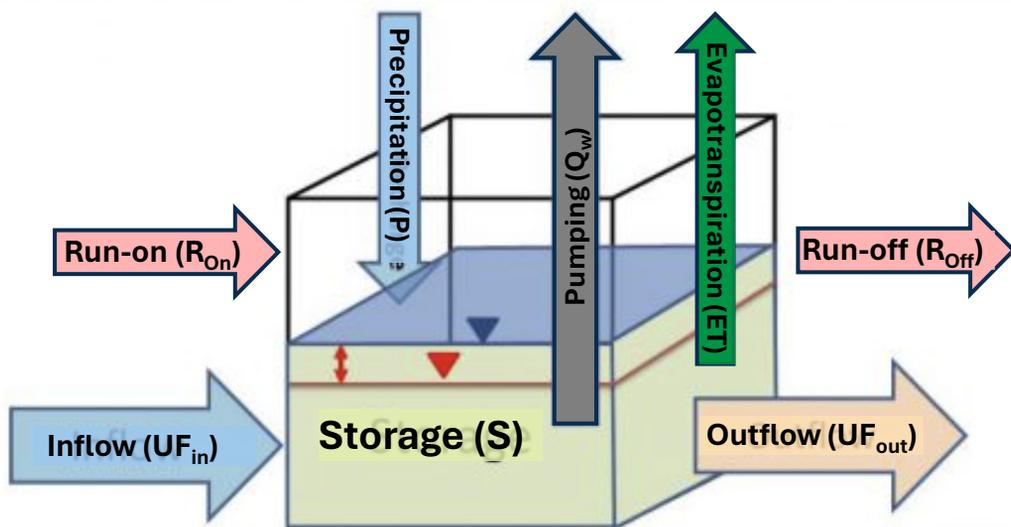


SOURCE(S):

Table: IWVGA GSP (2020)

Figure: Modified after Ramboll (2024) Total annual production 1980-2023

SVM: Searles Valley Minerals, IWVWD: Indian Wells Valley Water District, MDBK: Meadowbrook Dairy; MP: Mojave Pistachio, Navy: Naval Air Weapons Station China Lake, Navy non-potable refers to a single production well in the north of IWV Basin, Non- de minimis pumping includes other small agricultural pumping and other non-domestic and non-mutual pumping.

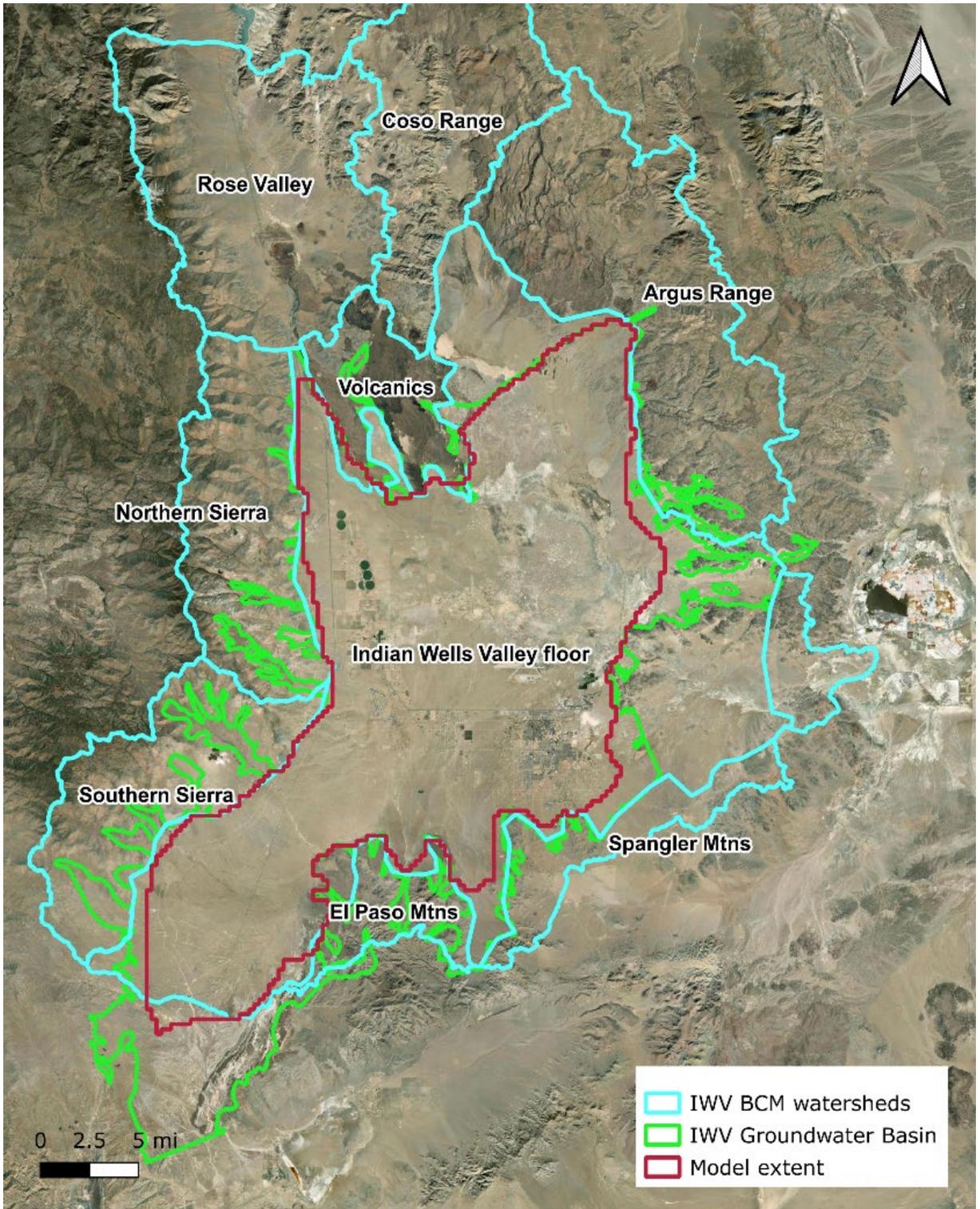


SOURCE(S):

Modified after HydroSimulatics, Inc (<https://www.magnet4water.net/Home.aspx>)

Note: anthropogenic recharge is not shown because this involves many factors yet is small compared to natural recharge.

Figure 3-8: Water Budget Schematic



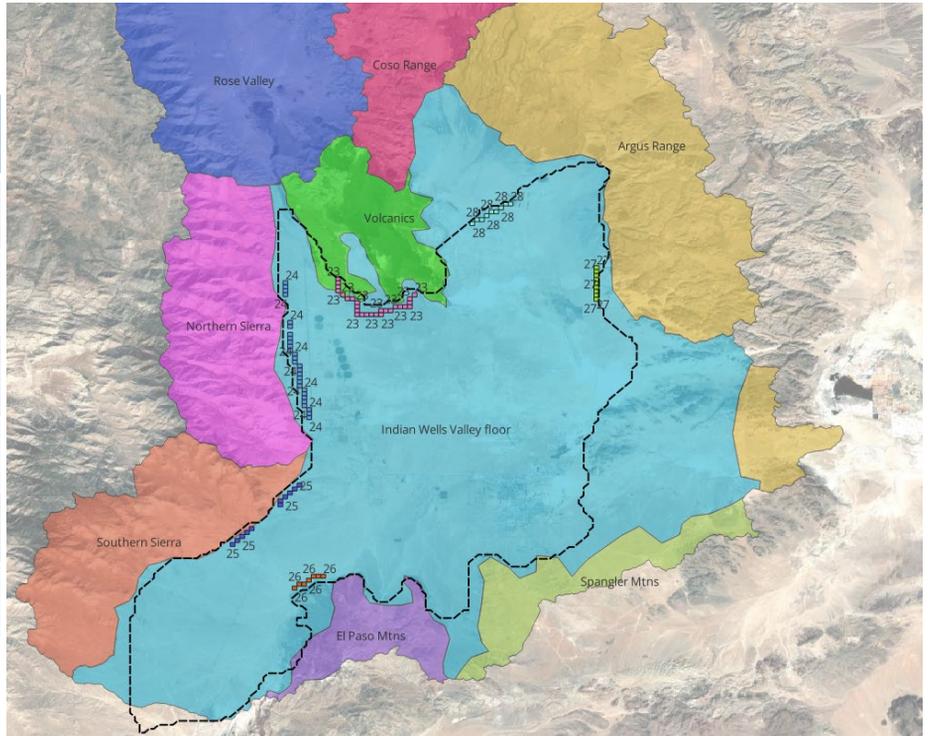
SOURCE(S):
Modified after Ramboll (2025)

IWWWD 0000006272

Figure 4-1: Ramboll Model Domain (after Ramboll, 2025)

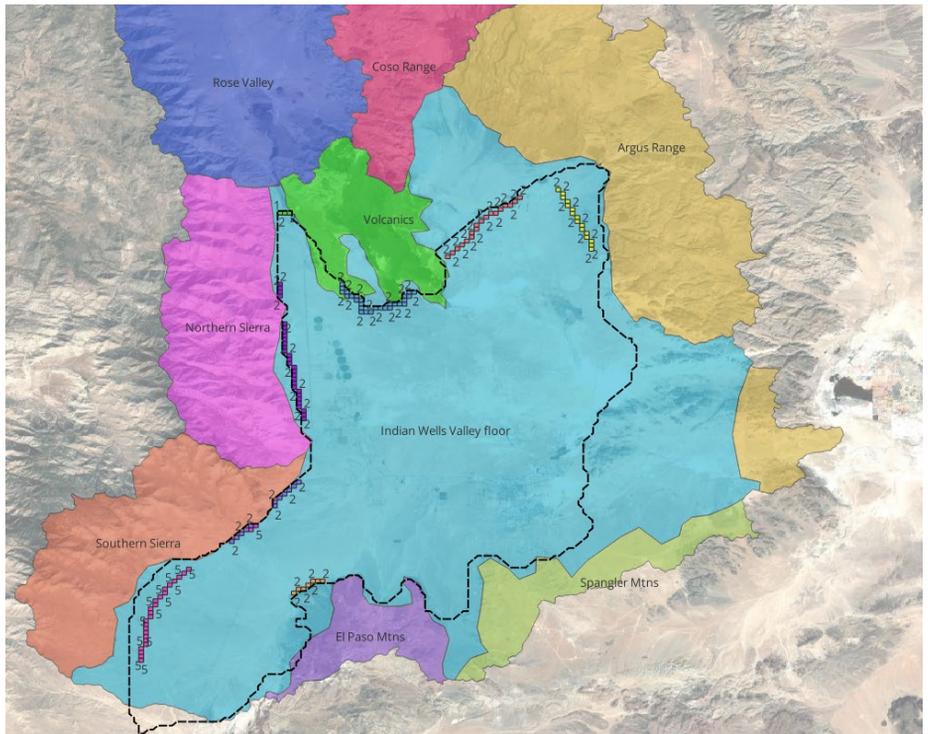
BCM Run-off

Recharge zone	Sub-watershed
23	Volcanics
24	Northern Sierra
25	Southern Sierra
26	El Paso Mtns
27	Argus Range
28	Coso Range



BCM Recharge

Well reach	Sub-watershed
90	Rose Valley*
91	Volcanics
92	Northern Sierra
10	Southern Sierra
11	El Paso Mtns
12	Argus Range
13	Coso Range
14	Southern Sierra



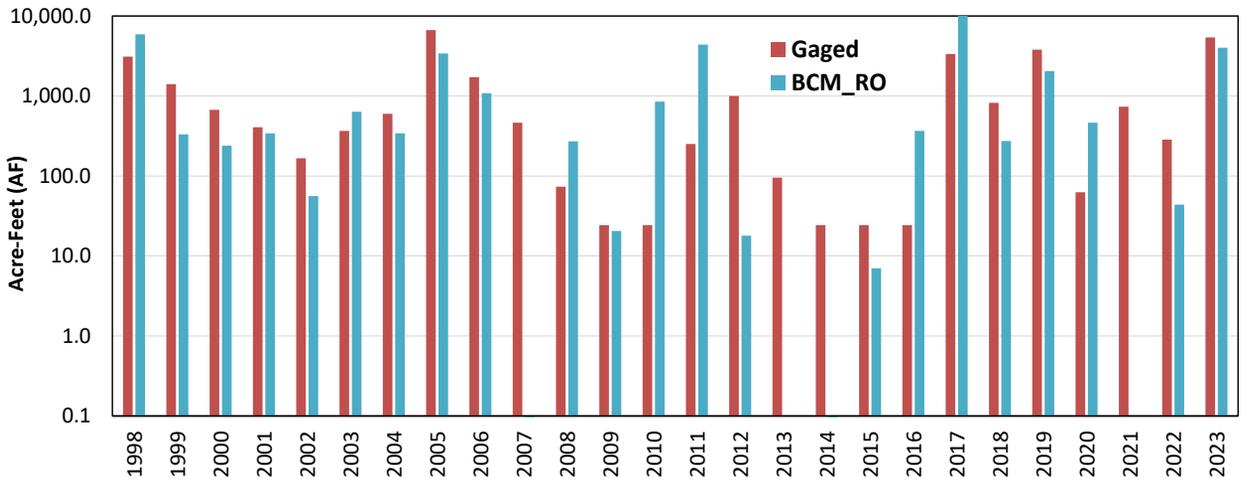
SOURCE(S):

Ramboll Model (2025), Prepared by SSP&A

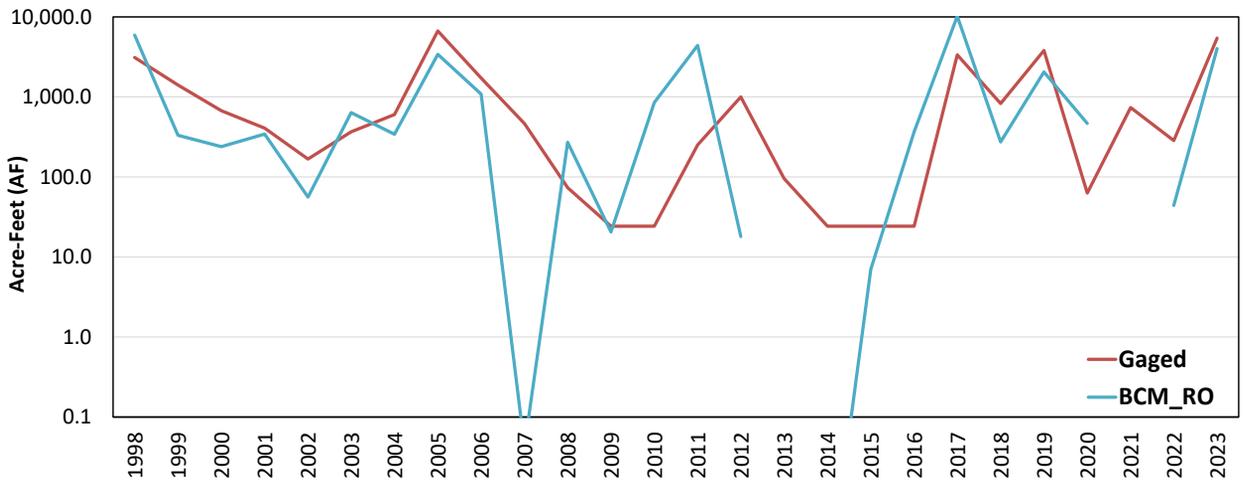
*Rose Valley recharge prescribed as detailed in the report

Figure 4-2: Primary Locations of Groundwater Recharge as Represented in the Ramboll Model

Bar Chart



Line Chart



SOURCE(S):

Prepared by SSP&A from BCMv8 outputs and available streamflow data.

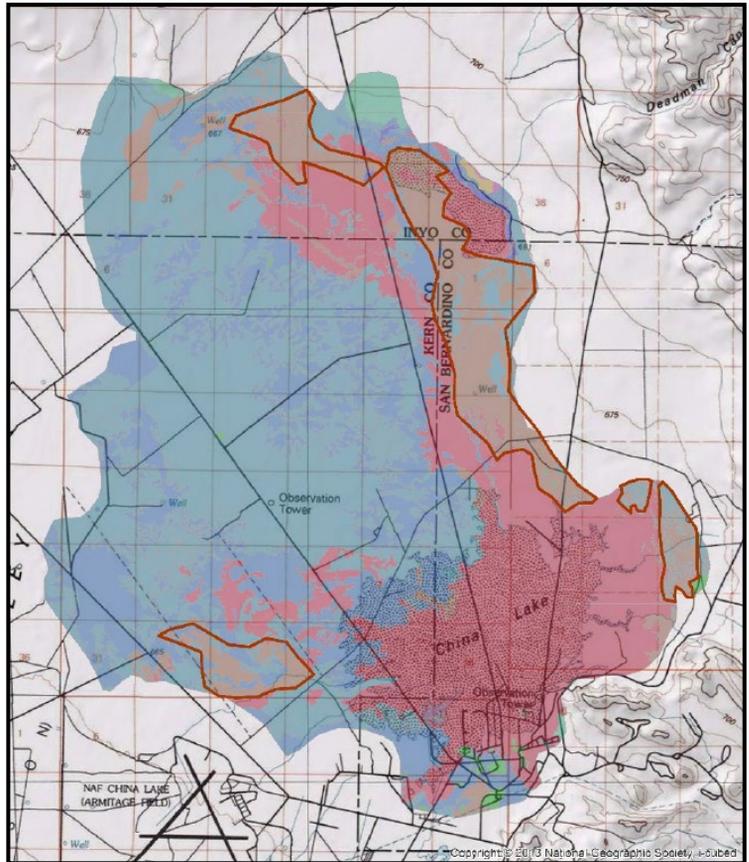
Gaged streamflow with Nine Mile Stream estimated and BCM calculated runoff.

Figure 4-3: Graphical Comparisons of Gaged and Calculated Streamflow for the Northern Sierra

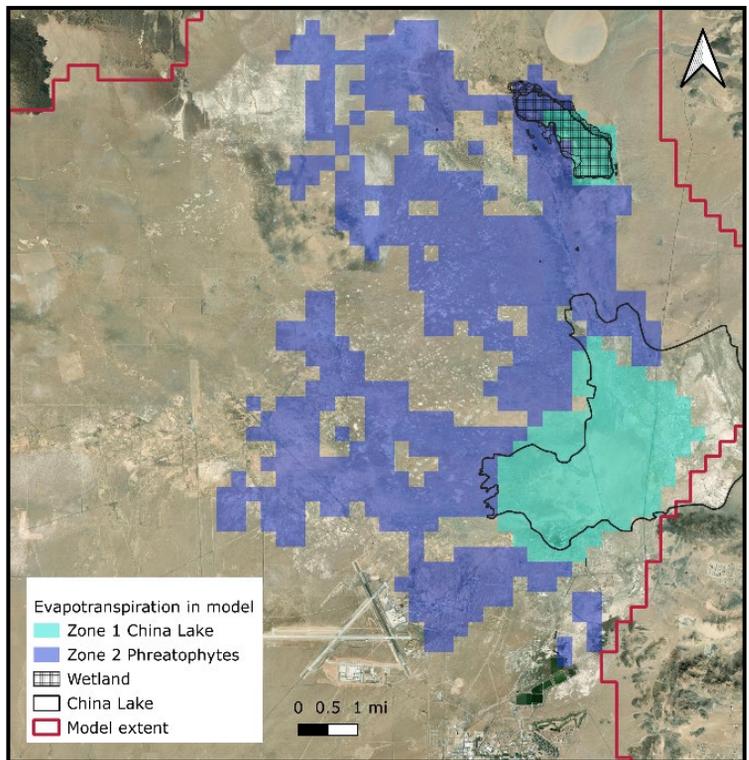
Distribution of vegetation and bare ground within the ET area

Legend

-  Greasewood Outline
- Vegetation Class**
-  Alkaline Mixed Grasses and Forbs
-  Alkaline Mixed Scrub
-  Barren
-  Creosote Bush
-  Greasewood
-  Pickleweed-Cordgrass
-  Rabbitbrush
-  Shadscale
-  Tule-Cattail
-  Urban or Developed
-  Water (General)
-  White Bursage

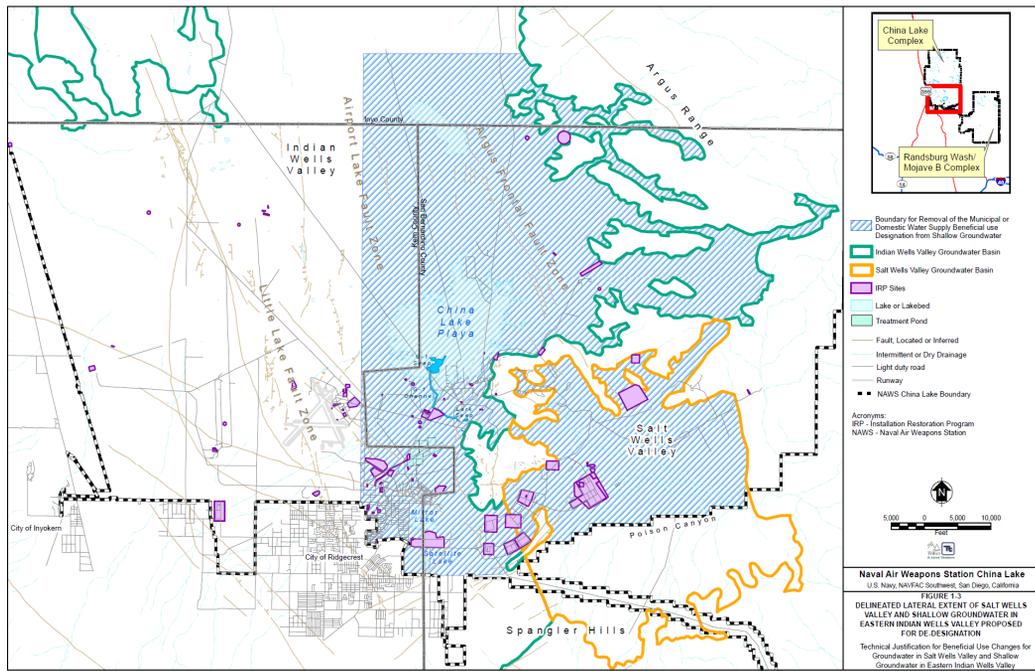


Spatial distribution of ET cells in the Ramboll Model



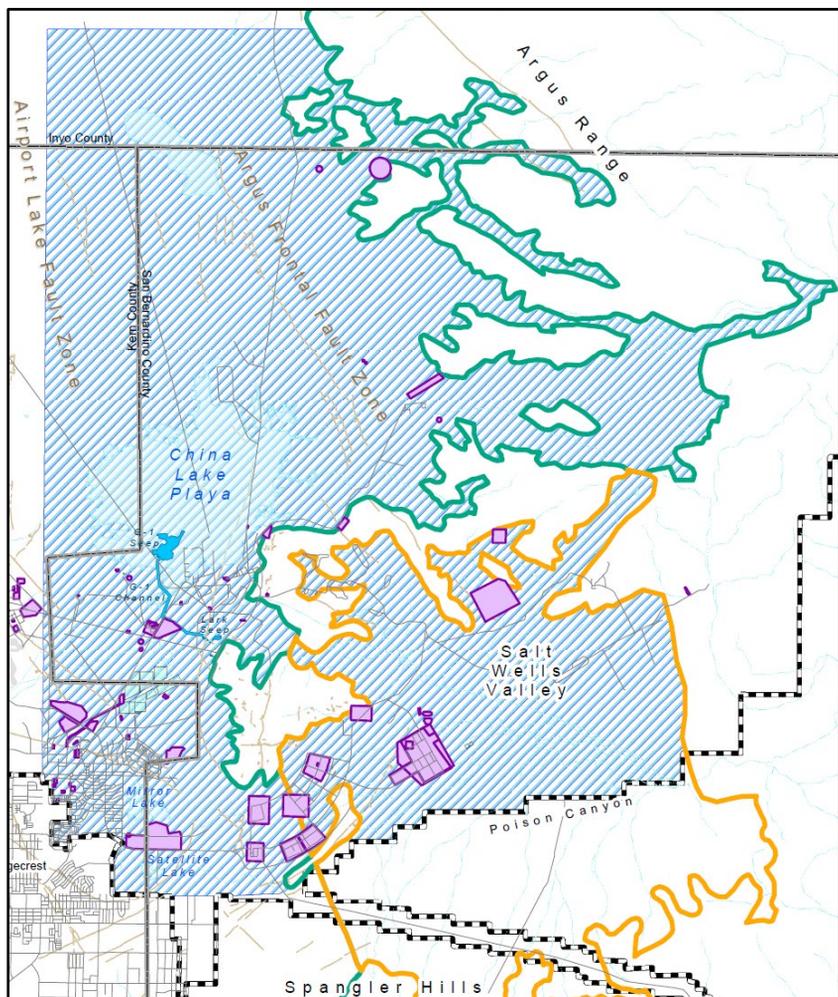
SOURCE(S):
 Upper image: Modified after NAWCWD TP 8811 (2016) Figure 15
 Lower Image: Modified after Ramboll (2025)

Figure 4-4: Primary Areas of Evapotranspiration (ET): (a) Historical Map, and (b) Representation in Ramboll Model



Upper image:
excerpt from
TriEcoTt (2013)

Lower image:
zoom to proposed
de-designation
area



SOURCE(S):
Modified after TriEcoTt (2013)

Figure 4-5: Delineated Area for De-Designation IWWVD 000006276

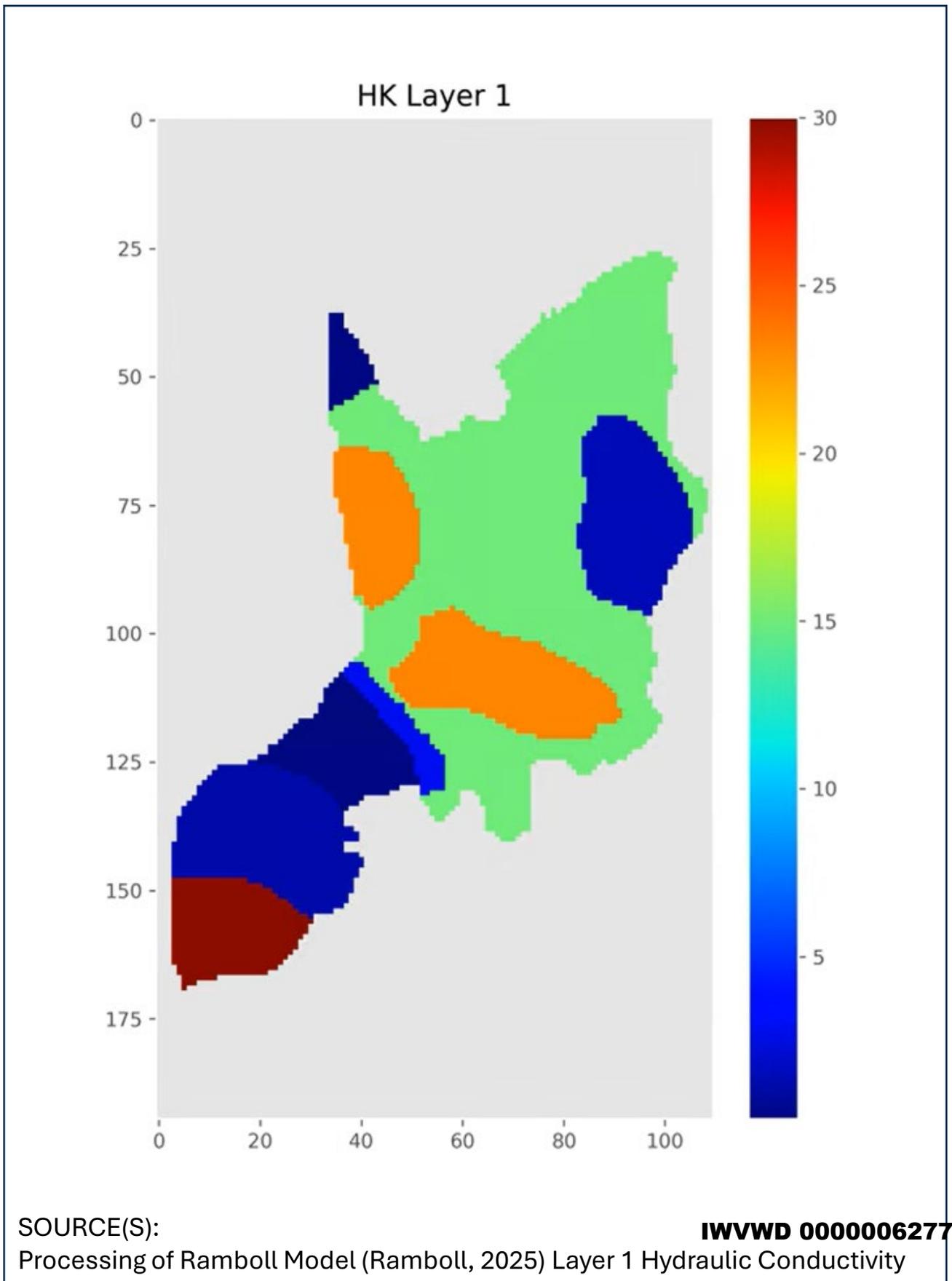
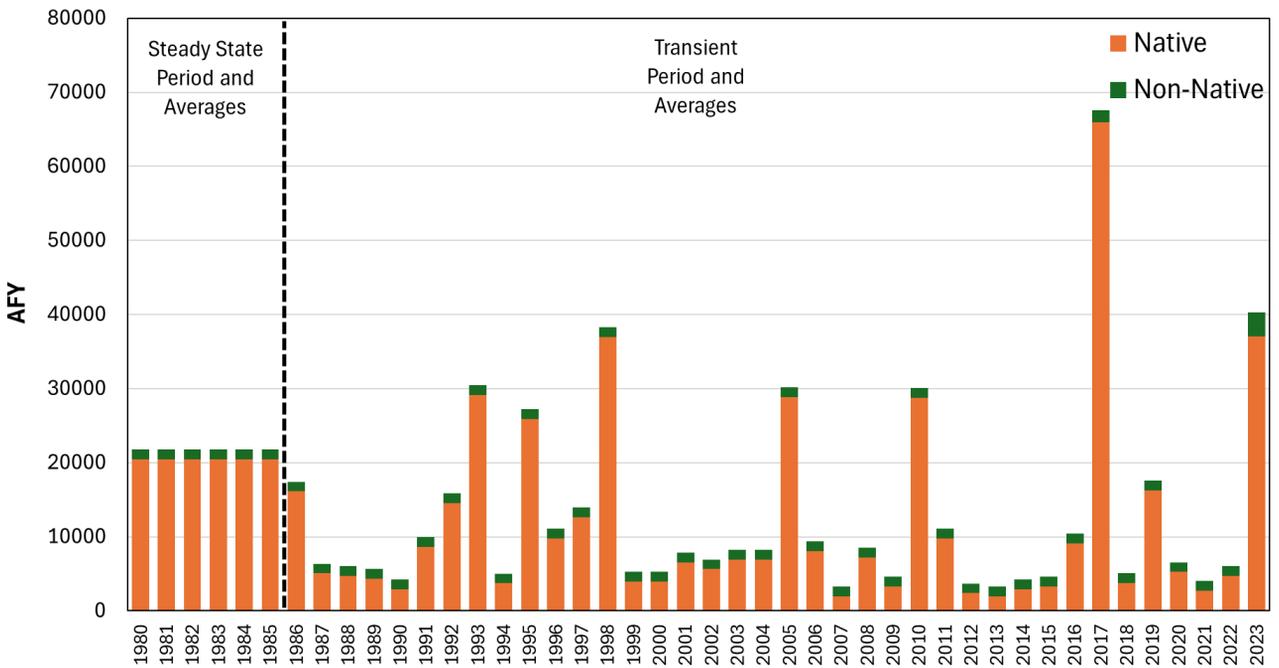


Figure 4-6: Example Image of Aquifer Parameter Zonation



SOURCE(S):
 Processing of input files to Ramboll Model (Ramboll, 2025)

Figure 4-7: Total Recharge Rates and Fractions for the Period 1980-2023

TABLES

YEAR	STORAGE	PUMPING	RECHARGE (VIA "WEL")	RECHARGE (VIA "RCH")	RECHARGE (TOTAL)	ET
SS	0	-19333	16822	4819	21641	-2307
SS	0	-19333	16822	4819	21641	-2307
SS	0	-19333	16822	4819	21641	-2307
SS	0	-19333	16822	4819	21641	-2307
SS	0	-19333	16822	4819	21641	-2307
SS	0	-19333	16822	4819	21641	-2307
1986	13817	-28945	13238	4197	17435	-2306.7
1987	20546	-24603	3612	2748	6360	-2303
1988	20615	-24313	3234	2760	5994	-2296
1989	21610	-24999	2890	2786	5675	-2285
1990	21633	-23546	1593	2591	4184	-2270
1991	15151	-22879	7012	2971	9983	-2254
1992	9493	-23110	12398	3456	15854	-2236
1993	-4023	-24213	26301	4155	30455	-2220
1994	21905	-24728	2159	2871	5029	-2206
1995	-229	-24774	23166	4028	27194	-2191
1996	15873	-25122	8146	3301	11448	-2199
1997	11697	-24288	11309	3444	14754	-2163
1998	-10160	-24815	31963	5162	37124	-2149
1999	18918	-22078	2671	2626	5298	-2137
2000	20377	-23576	3136	2185	5321	-2122
2001	17538	-23162	5549	2180	7729	-2105
2002	17868	-22855	4946	2128	7074	-2086
2003	18051	-24147	6000	2162	8162	-2066
2004	17242	-24267	6715	2355	9071	-2045
2005	-4593	-22785	25764	3640	29404	-2025
2006	17893	-25052	6718	2450	9168	-2009
2007	24468	-25900	1159	2266	3425	-1991
2008	18777	-25166	6004	2356	8360	-1970
2009	22684	-25569	2419	2416	4835	-1948
2010	-5354	-22782	26167	3892	30059	-1923
2011	13797	-22679	8396	2384	10780	-1898
2012	23066	-24856	1397	2290	3687	-1897
2013	23480	-24871	942	2300	3242	-1849
2014	26259	-28591	1599	2555	4154	-1821
2015	23743	-26903	2467	2484	4951	-1790
2016	13274	-26634	12229	2889	15118	-1757
2017	-36691	-23991	56130	6280	62410	-1728
2018	18874	-23089	3701	2222	5923	-1708
2019	6707	-21654	13851	2785	16636	-1689
2020	17562	-22164	4061	2212	6273	-1670
2021	19636	-22108	2042	2080	4123	-1650
2022	15855	-22088	5608	2254	7862	-1629
2023	-16297	-20235	32566	5539	38105	-1573

SOURCE(S):

Processing of output files from Ramboll Model (Ramboll, 2025)

IWVWD-000006280

Table 4-1: Simulated Water Budgets for the Period 1980-2023

Period	Safe Yield		Notes
	With ET	Without ET	
AVG (2011-2015)	3512	5363	GSP (IWVGA, 2020) yield estimate period
AVG (2014-2023)	14854	16556	TWG (2024) yield estimate period
AVG (1980-2023) (INC SS)	12329	14375	Average with steady state years

Table 4-2: Results of Yield Calculations

YEAR	Native	Non-Native	Total
1980	20451	1319	21770
1981	20451	1319	21770
1982	20451	1319	21770
1983	20451	1319	21770
1984	20451	1319	21770
1985	20451	1319	21770
1986	16123	1319	17441
1987	5048	1319	6367
1988	4682	1319	6001
1989	4363	1319	5682
1990	2872	1319	4190
1991	8671	1319	9990
1992	14543	1319	15861
1993	29119	1319	30437
1994	3717	1319	5036
1995	25870	1319	27188
1996	9737	1319	11056
1997	12608	1319	13927
1998	36927	1319	38246
1999	3981	1319	5300
2000	3937	1319	5255
2001	6508	1319	7827
2002	5633	1319	6951
2003	6900	1319	8219
2004	6893	1319	8212
2005	28883	1319	30201
2006	8043	1319	9362
2007	1941	1319	3260
2008	7183	1319	8501
2009	3274	1319	4592
2010	28748	1319	30067
2011	9747	1319	11065
2012	2383	1319	3702
2013	1936	1319	3255
2014	2871	1319	4189
2015	3270	1319	4589
2016	9116	1319	10435
2017	65909	1632	67541
2018	3751	1319	5069
2019	16234	1319	17553
2020	5253	1319	6571
2021	2721	1319	4040
2022	4702	1319	6020
2023	37023	3223	40247
Subtotals	573830	60238	634067
Percents	90.5%	9.5%	n/a

SOURCE(S):

Processing of input files to Ramboll Model (Ramboll, 2025)

Table 4-3: Total Recharge Rates and Fractions for the Period 1980-2023

APPENDICES

Matthew J. Tonkin, Ph.D.

President and Principal Hydrogeologist

As President, Dr. Tonkin manages or advises on many projects. He specializes in data synthesis and modeling to guide groundwater, surface water, soil and contamination studies, for public, private and legal clients. This includes planning sampling and monitoring programs; collaborating with other experts; developing and applying models; and presenting to stakeholders. He received his PhD on the topic of model calibration and uncertainty analysis under Dr. John Doherty and has instructed on these and other topics.

REPRESENTATIVE EXPERIENCE

S.S. Papadopoulos & Associates, Inc.

U.S. Navy Red Hill Fuel Storage Facility, Hawaii: In accordance with an Administrative Order on Consent (AOC), assisted EPA and Hawaii DOH in evaluating the conceptual site model (CSM); interpreting soil, soil vapor, fuel product, and groundwater data; and the development by the Navy and its contractors of saturated and vadose zone flow and transport models for the complex fractured basalt aquifer overlain and intruded by volcanics. Led forensic evaluations of environmental data including analyses of gas chromatograms, and evaluations of PFAS/PFOA compounds associated with AFFF facilities. Undertook spatial and temporal statistical analyses. Developed model review criteria; presented at multiple in-person and remotely hosted stakeholder meetings; provided written technical comment on Navy deliverables. Provided additional technical support in response to documented releases to the environment that occurred in 2021, and more recently provided technical support in developing monitoring and response strategies for defueling of the facility.

Private Client, San Francisco, California: Led evaluation of risk posed to two high-capacity supply wells by fuel released from a storage facility. Simulated multi-component vadose- and saturated-zone transport of the BTEX compounds, MTBE, TBA, and less soluble components. Implemented kinetic transport capabilities developed by SSP&A under contract to USEPA as released in the MT3D-USGS transport simulation code.

Confidential Client, California: Assessed the fate and transport of several contaminants including chlorinated solvents, chromium, and 1,4-dioxane in groundwater from numerous sources, as part of a multi-party allocation at a large Superfund site within a mixed residential-/commercial-use area. Provided technical support to ultimately conclusive mediation proceedings.

Confidential Client, Maryland: Retained to evaluate the fate of Cr[VI] arising from historical plating at this RCRA corrective action facility, and interpret the effectiveness of various remedies. Delineation comprised vertical delineation borings (VDBs) and nested wells, and Cr[VI] remedies included enhanced fluid recovery (EFR) and in-situ chemical reduction (ISCR). SSP&A evaluated the EFR and ISCR using multi-variate trend analysis, data mapping, and reactive transport modeling. Provided guidance in the delineation and mobility-assessment of light non-aqueous phase liquid (LNAPL) and its soluble fractions; and evaluated the sources, transport and fate of chlorinated volatile organic compounds (cVOCs). Evaluated the potential for PFAS/PFOA compounds to be presented based on facility manufacturing and material use information. Participated in numerous remotely hosted and in-person meetings with the EPA, including application of the RCRA FIRST (Facilities Investigation Remedy Selection Track) toolbox for site evaluation and remedy selection,



YEARS OF EXPERIENCE

25+

EDUCATION

- » **PhD**, Civil Engineering, University of Queensland, Australia, 2009
- » **MSc**, Hydrogeology, University of Birmingham, UK, 1994
- » **BSc**, Applied Geology, University of Birmingham, UK, 1993

EXAMPLE AREAS OF EXPERTISE

- » Groundwater Remedy Design
- » Groundwater Flow and Contaminant Transport Simulation
- » Environmental Data Analysis and Interpretation
- » Modeling Project Design and Management
- » Water Resource Evaluations
- » Model Calibration and Uncertainty Analysis

AWARDS AND HONORS

- » Co-Inventor of U.S. Patent No. 10,371,860 (issued Aug. 6, 2019), entitled "*Simultaneous Multi-Event Universal Kriging Methods for Spatio-Temporal Data Analysis and Mapping*": 2019
- » ITRC Industry Recognition Award (co-recipient) – MTBE and other Fuel Oxygenates Team: 2005
- » NGWA Outstanding Groundwater Remediation Project Award (co-recipient): 2004
- » ENTEC Award for MS Program and Thesis: 1994
- » British National Environmental Research Council (NERC) MS scholarship: 1993

culminating in SSP&A leading the development of a long-term monitoring (LTM) plan to support a Statement of Basis. The LTM work guided data collection to support MNA as the final groundwater remedy with source removal, natural source zone depletion (NSZD), and a restrictive land use covenant.

Goleta Groundwater Basin, California: Retained to provide hydrogeological and modeling services in legal proceedings as an affirmative and responsive expert establishing quantities of water available for allocation / adjudication as via a Physical Solution. Developed a detailed understanding of the hydrogeology of the Goleta Groundwater Basin (GGWB) and surrounding and underlying consolidated bedrock units, and conducted simulations using groundwater flow, integrated hydrologic, and land-surface process models constructed with Modflow, Modflow-Surfact, ParFlow-CLM, Hydrus, the Soil Water Balance (SWB), INFIL, PRMS, and the Distributed Parameter Watershed Model (DPWM). A major component of the work comprised distinguishing and estimating potential and actual groundwater recharge.

U.S. EPA Region 5: Provided multi-year technical support to Region 5 EPA Superfund group evaluating remedy decisions and actions under CERCLA. Scope includes evaluating conceptual site models (CSMs); interpreting regulatory documents focused on remedy decisions; reviewing or developing analyses of groundwater flow, contaminant transport, and the sources, disposition, and remediation of primary and secondary sources; with the overarching objective of evaluating and improving the performance of remedies at >30 Superfund sites. Authored / co-authored reports to support Five-Year Reviews, with recommendations on remedy and monitoring optimization. Remedial technologies evaluated included pump-and-treat (P&T), monitored natural attenuation (MNA), slurry/barrier walls, in-situ reduction/oxidation, and soil vapor extraction (SVE), among others. Oversaw sampling and characterization activities for PFAS/PFOA compounds at two selected sites based on past manufacturing and reporting chemical use histories. Led a rigorous comparative monitoring network evaluation and optimization study using Summit Optimizer, MAROS, VSP, indicator cross-validation, and maximum likelihood methods.

U.S. DOE Hanford Site, Washington State: Over 15 years as part of a multi-firm team addressing radionuclide, organic and inorganic contamination under CERCLA, RCRA, and AEA programs. Developed fate-and-transport models for remedy design and optimization of Central Plateau and River Corridor OUs. Developed and documented methods and guidelines to assess remedy performance and conducted a “needs assessment” for model-based decision support. Developed methods to assess remedy performance and simulated Uranium, Iodine, Sr90, Tc-99, CrVI, TCE, NO3, CCl4 and other constituents, as part of CERCLA and RCRA actions. Developed and published multi-variate trend analyses for MNA remedies. Oversaw sitewide RCRA facility and monitoring network evaluations and the development of monitoring and data analysis strategies during the transition of dozens of RCRA facilities from interim to final monitoring status. Presented findings at numerous multi-stakeholder meetings.

New York Department of Environmental Conservation: Provided hydrogeologic oversight and groundwater flow and fuel-component transport and fate analyses to design and optimize soil and groundwater remedies to protect sole-source municipal supplies from single and multiple UST releases at over 15 facilities. Designed and implemented sentinel monitoring network programs for municipal supplies. Presented results at public/civic meetings, ITRC events, and a remediation charette throughout New York State. Co-recipient of NGWA groundwater remediation award for work at the Hampton Bays site.

Continued from previous page

- » Individual Structural Geological Mapping Award: 1993
- » Royal Air Force Flight Training Scholarship: 1988

APPOINTMENTS AND COMMITTEES

- » 2021–present: Groundwater Resources Association of California (GRAC) GRACast Subcommittee
- » 2013–2024: MODFLOW-and-More Conference Organizing Committee: Colorado School of Mines, Princeton
- » 2018, 2019: Groundwater Journal, Guest Editor
- » 2005–2010: Interagency Steering Committee on Multimedia Environmental Models (ISCMEM)
- » 2002–2006: Interstate Technology and Regulatory Council (ITRC) MTBE Team

PROFESSIONAL SOCIETIES

- » National Ground Water Association (NGWA)
- » Geological Society of America (GSA)
- » Groundwater Resources Association of California (GRAC)
- » American Geophysical Union (AGU)

PROFESSIONAL HISTORY

- » S.S. Papadopoulos & Associates, Inc.: 1995–present
- » Birmingham University, UK, Geology Department: 1993–1994

EMAIL

matt@sspa.com

Delta Consultants (on behalf of BP), Deer Park, New York: Analyzed the distribution and transport of multiple contaminants arising from a fuel-spill migrating toward a large freshwater body to support investigation efforts and a comparative evaluation of remedial alternatives. Presented results to New York State Department of Environmental Conservation.

Otis Air Force Base, Massachusetts: Retained to design performance monitoring plans for several pump-and-treat systems under CERCLA including evaluation of the location, migration, and impacts of CVOCs and other constituents discharging to freshwater kettle ponds. Contributed to treatment plant design assessments, recommended O&M improvements, and co-authored quarterly and annual reports. Designed and oversaw data collection activities including impeller and heat-pulse flow profiling of long-screened extraction wells to identify contaminant inflow locations and estimate aquifer parameters. Developed novel data mapping techniques as a supplement to numerical groundwater flow and contaminant transport modeling. Presented technical findings to AFCEE and at multi-stakeholder meetings. To undertake this work efficiently, made primary residence in Barnstable County from 1999 through 2004.

West Lake Superfund Site, Missouri: Led an assessment of the lateral and vertical extent, disposition, and potential transport and fate of radionuclides within and from solid landfill water materials. Implemented 3D multiple-indicator geo-statistics using a variety of data types to assess radionuclide extent and partial excavation strategies, and managed a project team participating in field work, lab studies and geochemical fate and transport modeling.

WATER RESOURCE EVALUATIONS

Water Resource Assessment, Minnesota: Retained by MDNR to evaluate groundwater and surface water conditions, including modeling and statistical studies conducted by the USGS and others, and provide an expert opinion on the impact of groundwater extraction on surface water.

Confidential Client, California: Evaluated groundwater budgets, and the transport, extent, and mixing of produced water in the subsurface using a variety of time-series and geochemical analysis, geo-statistics, and deterministic modeling techniques.

Saline Incursion Management, Washington State: To evaluate the sustainability of a water resources that is subject to salinity incursion and upconing, participated in the development of a variable-density model, and led the design and implementation of a transient calibration strategy that included water levels and salinities. Used the calibrated model to estimate optimal pumping rates to meet drinking water criterion for chloride at existing and proposed production-well locations.

California Department of Water Resources (CA-DWR): In collaboration with Woodward & Curran, developed conceptual and numerical modeling bases, calibration approach, and stream-depletion analysis methods, for three Central Valley models – the Sacramento Valley (SVSIM), and the coarse- and fine-grid full Central Valley applications (C2VSIM-CG and C2VSIM-FG). This included developing methods and tools to integrate sediment texture into model development and parameterization (Texture2Par); implementing time-series and correlative analysis for groundwater elevation and streamflow targets; leading calibration of the three models; and preparing methods of historical and predictive streamflow depletion analysis.

California Department of Water Resources (CA-DWR): In collaboration with CH2M-Hill, created and modified programs to calibrate the IGSM2 code Central Valley application (CVGSM2) during its transition to the IWFM platform. Reviewed existing USGS and CA-DWR models and reports to support model re-structuring and re-parameterization. Re-defined aquifer parameters using pilot points; completed sensitivity analyses with the revised model to guide calibration; co-authored reports outlining a stepwise model development and calibration strategy.

Spring-water Bottling Company Water Supply Study, Michigan: Evaluated possible impacts of groundwater pumping on surface water bodies including wetlands. Following calibration of a groundwater model to baseflow data, and steady state and transient water levels, designed a series of non-linear predictive error analyses to assess uncertainties in predicted depletions. Conducted similar analysis at several potential spring sources over several years.

Republican River Basin Interstate Compact: Provided technical evaluation of the nature, magnitude and timing of streamflow accretions and depletions through the development of a calibrated model. Calibration data included transient water-level and stream-flow calibration targets. Implemented pilot points with regularization for aquifer parameters, and evaluated a mixed-model ANOVA applied to power conversion coefficients (PCCs) as a surrogate for metered pumping. Supported testimony before a River Master and in Supreme Court.

EXAMPLE DATA ANALYSIS PROJECTS

Marion Thompson Site, Indiana: Completed Monte-Carlo analyses of contaminant transport in groundwater combining bootstrap re-sampling, published PDFs, and re-parameterization techniques to represent variables for this probabilistic evaluation of fate-and-transport.

PCB-Contaminated Site: For a confidential private client, reviewed 1100 chromatographs to characterize source area, receptor stream and sediment signatures. Wrote

programs to plot, scale, and align chromatographs based on curve area, height and lab spikes. Developed cumulative-area method to identify contributions at receptors as part of an allocation process.

Big South Fork National Park, Kentucky: Assessed contaminant load to a river from 80 mines. Coordinated field sampling tasks. Completed data QA/QC, analyses and interpretation. Simulated mine water mixing using Phreeqc. Prepared STORET database for the National Park Service.

Confidential Client, San Francisco, California: To support soil removal actions, wrote programs to process numerous look-up tables, using varying assumptions for censored data, to calculate, summarize, and compare 95% UCLs for the mean for over 30 analytes.

PROGRAMMING & SOFTWARE DEVELOPMENT

Release of MT3D-USGS: Contributing developer to MT3D-USGS, incorporating multi-component transport capabilities developed for EPA plus other features (Documented in Bedekar *et al.*, 2016).

Expansion of HSSM and MT3DMS to Simulate Multi-Species Reactive Transport: Contracted by USEPA-ORD to expand HSSM and MT3DMS to simulate kinetic reactive transport of multiple fuel constituents with application to fuels. Capability ultimately released in MT3D-USGS.

Linkage of HSSM with MT3DMS: Contracted by the USEPA-ORD, with Dr. Chunmiao Zheng, to link vadose simulation capabilities of HSSM to MT3DMS and provide calibration support with PEST. Developed software released in 2010 (Documented in Zheng *et al.*, 2010).

Data Worth Evaluation Using Models: Contracted by the U.S. Geological Survey to program OPR-PPR, which uses FOSM methods and the JUPITER API to evaluate the relative importance of observations and information on model parameters to predictions (Detailed in Tonkin *et al.*, 2007).

Predictive Analysis with MODFLOW: Contracted by the USGS to program MOD-PREDICT, which executes MODFLOW-2000 forward, performs sensitivity and calibration runs, and calculates summary statistics focused on predictive error analysis. (Documented in Tonkin *et al.*, 2003).

Hydraulic Capture Analysis: Co-developer of KT3D_H2O programs that combine kriging, analytic elements and particle tracking to map groundwater levels and evaluate hydraulic capture. (Documented in Karanovic *et al.*, 2009; Tonkin *et al.*, 2009; Tonkin and Larson, 2002.)

TRAINING & SOFTWARE SUPPORT

MODFLOW and More Conferences: Member of organizing committee, Integrated Groundwater Modeling Center (IGWMC), Colorado School of Mines (2013, 2015, 2017, 2019, 2022).

The PEST Conference: Principal organizer and editor of electronic proceedings for model calibration and uncertainty analysis. Published on-line at LULU.com (November 2009).

Collection and Mapping of Water Levels to Assist in Remedy Performance Evaluation: Organizer, co-instructor. Presented to USDOE and contractors at the Hanford Site (August 2009).

PEST Software Support: Provided technical support for the software PEST through a list-serve hosted by S.S. Papadopoulos & Associates, Inc. (2002–2012). Organizer and Instructor (with Dr. John Doherty) of model parameterization and uncertainty analysis courses using PEST in the USA and overseas (2002–present).

Instructor (with Dr. Mary Hill) of “UCODE_2005 and Pest: Universal Inversion Codes for Automated Calibration” (2006, 2007, 2009, 2011); “Programming with the JUPITER-API” (2008).

ITRC Workshop Instructor: “MTBE & TBA Comprehensive Site Assessment and Successful Groundwater Remediation”. New York (2003), Denver (2004), San Francisco (2005).

Structural Mapping Supervisor: Birmingham University, United Kingdom. Assisted professors in developing mapping training for introduction to curriculum (1994).

Publications & Presentations

DiFilippo, E., M. Tonkin and W. Huber, 2023. *Use of Censored Multiple Regression to Interpret Temporal Environmental Data and Assess Remedy Progress*. Groundwater, vol 61, no. 6: 846-864. doi: 10.1111/gwat.13315

Wyatt, K., M. Beck, and M. Tonkin, 2022. *Advanced Geostatistics to Optimize the Sampling Approach for Contaminated Soil Investigations and Remediations*. Platform presentation at Battelle’s Twelfth International Conference on Remediation of Chlorinated and Recalcitrant Compounds. May.

Muffels, C., S. Panday, C. Andrews, M.J. Tonkin, and A. Spiliotopoulos, 2022. *Simulating Groundwater Interaction within a Surface Water Network using Connected Linear Networks (CLNs)*. Ground Water. doi: 10.1111/gwat.13202. Online release April.

Tonkin, M.J., and M. Chowdhury, 2022. *Groundwater Modeling to Support Site Characterization and Remediation in Field Sampling Methods for Remedial Investigations*. 3rd Edition.

Tonkin, M.J., and Chowdhury, M., 2021. *Monitoring Network Analysis for Integrated Central Plateau Decision Making (at the DOE Hanford Site)*. Invited Presentation at REMPLEx, the 2021 Global Summit on Environmental Remediation, November.

Tonkin, M.J., M. Hill, R.M. Maxwell, and C. Zheng, 2020. *Groundwater Modeling and Beyond: MODFLOW-and-More*. 2019 Special Issue. *Ground Water*, v. 58, no. 3, pp. 325-326, doi: [10.1111/gwat.12999](https://doi.org/10.1111/gwat.12999).

Spiliotopoulos A., E.L. DiFilippo, P. Khambhammettu, D. Hayes, M.J. Tonkin, M. Hartman, K. Iverson, and J. Hulstrom, 2019. *Web-Assisted Methods and Tools for Efficient Remedy Design and System Performance Evaluation at Hanford*. Presentation at the Waste Management Conference, Phoenix, AZ, March 7, 2019. Received “Superior” paper and “WM2019 Papers of Note Winner” awards. OSTI #23003084

DiFilippo E.L., M.J. Tonkin, A. Spiliotopoulos, W. Huber, and V. Rohay, 2019. *Evaluating Environmental Remediation Performance at Radwaste Sites Using Multiple, Censored Regression Analysis*. Presentation at the Waste Management Conference, Phoenix, AZ, March 7, 2019. IAEA #52043413

Maxwell, R.M., A. Navarre – Sitchler, and M. Tonkin, 2018. *Forward: Modeling for Sustainability and Adaptation*. *Ground Water*, v. 56, no. 4, pp. 515-516, doi: [10.1111/gwat.12795](https://doi.org/10.1111/gwat.12795).

Bedekar, V., E.D. Morway, C.D. Langevin, and M. Tonkin, 2016. *MT3D-USGS Version 1: A U.S. Geological Survey Release of MT3DMS Updated with New and Expanded Transport Capabilities for Use with MODFLOW*. U.S. Geological Survey Techniques and Methods Report #6-A53, Reston, VA. 69 p.

Tonkin, M.J., J. Kennel, W. Huber, and J. Lambie, 2015. *Multi-Event Universal Kriging (MEUK)*, *Advances in Water Resources*, v. 87, pp. 92–105, January. doi: [10.1016/j.advwatres.2015.11.001](https://doi.org/10.1016/j.advwatres.2015.11.001)

Royer, P. D., M.J. Tonkin, and T. Hammond, 2014. *Conjunctive Water Use in Confined Basalt Aquifers: An Evaluation Using Geochemistry, a Numerical Model, and Historical Water Levels*. *Journal of the American Water Resources Association (JAWRA)*, v. 50, No. 4, pp. 963–976, August. doi: [10.1111/jawr.12151](https://doi.org/10.1111/jawr.12151)

Tonkin, M.J., J. Kennel, W. Huber, and J.A. Lambie, 2013. *Hybrid Analytic Element Universal Kriging Interpolation Technique Built in the Open Source R Environment*.

Presentation at the American Geophysical Union, Fall Meeting 2013, Abstract #H52E-03.

Tonkin, M. and Z. Tajani, 2012. *Piecewise-Continuous Boundaries Using the MODFLOW FHB and MT3DMS HSS Packages*. *Ground Water*, v. 50, no. 2, pp. 296-300. doi: [10.1111/j.1745-6584.2011.00811.x](https://doi.org/10.1111/j.1745-6584.2011.00811.x)

Bedekar, V., C. Neville, and M. Tonkin, 2012. *Source Screening Module for Contaminant Transport Analysis Through Vadose and Saturated Zones*. *Ground Water*, v. 50, pp. 954–958. doi: [10.1111/j.1745-6584.2012.00954.x](https://doi.org/10.1111/j.1745-6584.2012.00954.x)

Ma, R., C. Zheng, J. Zachara, and M. Tonkin, 2012. *Utility of Bromide and Heat Tracers for Aquifer Characterization Affected by Highly Transient Flow Conditions*. *Water Resources Research*, v. 48, #8. doi: [10.1029/2011WR011281](https://doi.org/10.1029/2011WR011281)

Bedekar, V., R.G. Niswonger, K. Kipp, S. Panday, and M. Tonkin, 2011. *Approaches to the Simulation of Unconfined Flow and Perched Groundwater Flow in MODFLOW*. *Ground Water*, v. 50, no. 2, pp. 187-198. doi: [10.1111/j.1745-6584.2012.00811.x](https://doi.org/10.1111/j.1745-6584.2012.00811.x)

Ma, R., C. Zheng, M. Tonkin, and J. Zachara, 2011. *Importance of Considering Intraborehole Flow in Solute Transport Modeling under Highly Dynamic Flow Conditions*. *Journal of Contaminant Hydrology*, v. 123, Issues 1-2, April 1, 2011, pp. 11-19.

Hunt, R., J. Luchette, W. Schreuder, J. Rumbaugh, J. Doherty, M. Tonkin, and D. Rumbaugh, 2010. *Using a Cloud to Replenish Parched Groundwater Modeling Efforts*. *Ground Water*, v. 48, no. 3, pp. 360-365.

Shannon, R., M. Karanovic, and M. Tonkin, 2010. *Hydraulic Capture Estimated using Universal Kriging with Hydrologic Drift Terms*. Presentation at the 19th Annual Maryland Groundwater Symposium, Baltimore, MD, 47.

Tonkin, M.J. (Editor), 2010. *PEST Conference Proceedings*. Potomac, MD, November 2009. Available at www.LULU.com.

Zheng, C., J. Weaver, and M. Tonkin, 2010. *MT3DMS, A Modular Three-dimensional Multispecies Transport Model: User Guide to the Hydrocarbon Spill Source (HSS) Package*. Prepared for U.S. Environmental Protection Agency, Athens, GA.

Tonkin, M., and J. Doherty, 2010. *Citation and Acceptance of the 2009 M. King Hubbert Award*. *Ground Water* (published online). January 2010.

Tonkin, M., S. Dadi, and R. Shannon, 2009. *Collection and Mapping of Water Levels to Assist in the Evaluation of Groundwater Pump-and-Treat Remedy Performance*. SGW-42305 (Rev. 0). Prepared for the US Department of Energy, Richland, WA, September 2009.

Karanovic, M., M. Tonkin, and D. Wilson, 2009. *KT3D_H2O: A Program for Kriging Water-Level Data Using Hydrologic Drift Terms*. *Ground Water*, v. 45, no. 4, pp. 580-586, July/August. doi: [10.1111/j.1745-6584.2009.00565.x](https://doi.org/10.1111/j.1745-6584.2009.00565.x)

Tonkin, M. J., 2009. *Efficient Calibration and Predictive Error Analysis for Highly-Parameterized Models Combining Tikhonov and Subspace Regularization Techniques*. Doctoral Thesis, University of Queensland, Australia.

Weaver, J., J. Zhang, M. Tonkin, and R.J. Charbeneau, 2009. *Modeling the Transport of Ethanol Fuel Blends with the Combined HSSM and MT3D Models*. Presentation at the 21st Annual National Tanks Conference and Expo, Sacramento, CA, March 30 – April 01, 2009.

Tonkin, M., and J. Doherty, 2009. *Calibration-Constrained Monte Carlo Analysis of Highly-Parameterized Models Using Subspace Techniques*. *Water Resources Research*, v. 45. W00B10. doi: [10.1029/2007WR006678](https://doi.org/10.1029/2007WR006678)

Tonkin, M., C. Arola, and D. Miller, 2007. *Decision-Level Modeling within a Feasibility-Study Process: An Application at the Hanford Site*. Presentation at the Association of Engineering and Environmental Geologists 50th Anniversary, Los Angeles, CA, September 26-28, 2007.

Tonkin, M., and J. Doherty, 2007. *An Efficient Calibration-Constrained Monte Carlo Technique for Evaluating Model Predictive Uncertainty*. in Proceedings of an International Conference on Calibration and Reliability in Groundwater Modeling: Credibility of Modeling (ModelCARE2007), Copenhagen, Denmark, September 2007. IAHS Publication 320.

Hunt, R., J. Doherty, and M. Tonkin, 2007. *Are Models Too Simple? Arguments for Increased Parameterization*. *Ground Water*, v. 45, no. 3, pp. 254-262.

Tonkin, M., J. Doherty, and C. Moore, 2007. *Efficient Non-Linear Predictive Error Variance for Highly Parameterized Models*: *Water Resources Research*, v. 43. W07429. doi: [10.1029/2006WR005348](https://doi.org/10.1029/2006WR005348)

Tonkin, M., C. Tiedeman, D. Ely, and M. Hill, 2007. *OPR-PPR, a Computer Program for Assessing Data Importance to Model Predictions Using Linear Statistics, Constructed Using the JUPITER API*. Prepared in Cooperation with the U.S. Department of Energy. Techniques and Methods 6-E2. U.S. Geological Survey.

Muffels, C., H. Zhang, J. Doherty, R. Hunt, M. Anderson, and M. Tonkin, 2006. *Incorporating PROPACK into PEST to Estimate the Model Resolution Matrix for Large Groundwater Flow Models*. Presentation at the American Geophysical Union (AGU) Fall Meeting, Moscone Center, San Francisco, CA, December 2006.

Muffels, C., J. Doherty, M. Anderson, R. Hunt, T. Clemo, and M. Tonkin, 2006. *LSQR and Tikhonov Regularization in the Calibration of a Complex MODFLOW Model*. Presentation at the Geological Society of America Annual Meeting, Philadelphia, PA, October 2006.

Muffels, C., M. Tonkin, H. Zhang, M. Anderson, and T. Clemo, 2006. *Application of LSQR to Calibration of a MODFLOW Model: A Synthetic Study*. in Proceedings of MODFLOW and More 2006, Managing Ground-Water Systems, International Ground Water Modeling Center, Colorado School of Mines Golden, CO, May 2006, v. 1, pp. 283-287.

Tonkin, M., M. Karanovic, A. Hughes, and C. Jackson, 2006. *New and Contrasting Approaches to Local Grid Refinement*. in Proceedings of MODFLOW and More 2006, Managing Ground-Water Systems, International Ground Water Modeling Center, Colorado School of Mines Golden, CO, May 2006, v. 2, pp. 601-605.

Tonkin, M., and J. Doherty, 2005. *A Hybrid Regularized Inversion Methodology for Highly Parameterized Environmental Models*. *Water Resources Research*, v. 41, no. 10, October. W10412. doi: [10.1029/2005WR003995](https://doi.org/10.1029/2005WR003995)

Tonkin, M., and M. Becker, 2005. *Environmental Insite: A Software Package for Ground Water Data Visualization*. *Ground Water*, v. 43, no. 4, pp. 466-470. Software Spotlight.

Tonkin, M.J., 2005. *Model Analysis Using the JUPITER API*. Presentation at the Annual Public Meeting of the Interagency Steering Committee on Multimedia Environmental Models (ISCMEM), American Geophysical Union (AGU), Washington, DC, August 2005.

Tonkin, M., J. Weaver, C. Zheng, C. Muffels, and J. Rumbaugh, 2005. *Coupled Free and Dissolved Phase Transport: New Simulation Capabilities and Parameter Inversion*. in Proceedings of the 2005 National Ground Water Association (NGWA) Conference on MTBE and Perchlorate, Assessment, Remediation, and Public Policy, San Francisco, CA, May 2005.

Muffels, C., M. Tonkin, J. Haas, and D. Trego, 2005. *Predictive and Post-Audit Mass Flux Estimates*. in Proceedings of the National Ground Water Association (NGWA) Ground Water Summit, San Antonio, TX, April 2005.

Tonkin, M. (as Contributing author to Interstate Technology & Regulatory Council (ITRC)). MTBE and Other Fuel Oxygenates Team, 2005. *Overview of Groundwater Remediation Technologies for MTBE and TBA*. February 2005.

Neville, C. and M. Tonkin, 2004. *Modeling Multi-Aquifer Wells with MODFLOW*. *Ground Water*, v. 42, no. 6, pp. 910-919.

Tonkin, M. and C. Muffels, 2004. *Assessing Hydraulic Capture through Combined Analytic Elements and Interpolation*. EPA Groundwater Forum, Sacramento, CA, October 2004.

Tonkin, M., S. Larson, and C. Muffels, 2004. *Assessment of Hydraulic Capture through Interpolation of Measured Water Level Data*. Presentation at the Conference on Accelerating Site Closeout, Improving Performance, and Reducing Costs through Optimization: Environmental Protection Agency, Federal Remediation Technology Roundtable, Dallas, TX, June 2004.

Tonkin, M., T. Clemo, and J. Doherty, 2003. *Computationally Efficient Regularized Inversion for Highly Parameterized MODFLOW Models*. in Proceedings of MODFLOW and More 2003: Understanding through Modeling, International Ground Water Modeling Center, Colorado School of Mines, Golden, CO, September 16, 2003, v. 2, pp. 595-599.

Tonkin, M., M. Hill, and J. Doherty, 2003. *Modflow-2000, The U.S. Geological Survey Modular Ground-Water Model – Documentation of Mod-Predict for Predictions, Prediction Sensitivity Analysis, and Enhanced Analysis of Model Fit*. Prepared in Cooperation with the U.S. Department of Energy. U.S. Geological Survey Open-File Report 03-385.

Lolcama, J., H. Cohen, and M. Tonkin, 2002. *Deep Karst Conduits, Flooding, and Sinkholes: Lessons for the Aggregates Industry*. Engineering Geology, v. 65, no. 2-3, pp.151-157.

Tonkin, M., and S. Larson, 2002. *Kriging Water Levels with a Regional-Linear and Point-Logarithmic Drift*. Ground Water, v. 40, no. 2, pp. 185-193.

Neville, C., and M. Tonkin, 2001. *Representation of Multi-Aquifer Wells in MODFLOW*. in Proceedings of MODFLOW 2001 and Other Modeling Odysseys, International Groundwater Modeling Center, Colorado School of Mines, Golden, CO, September 2001, v. 1, pp. 51-59.

Cohen, H., M. Tonkin, and C. Neville, 2000. *Determination of Hydraulic Conductivity Distribution in a Heterogeneous Glacial Sand Aquifer: Correlation between Estimates Based on Impeller Flow Meter Data and Grain Size Distributions*. Society for Sedimentary Geology/International Association of Sedimentologists Research Conference: Environmental Sedimentology: Hydrogeology of Sedimentary Aquifers, Santa Fe, NM, September 24-27, 2000.

Deposition & Testimony-at-Trial Experience

DEPOSITIONS

- 2023 – *Jed and Alisa Behar v. Northrop Grumman Corporation and Northrop Grumman Systems Corp.*, United States District Court for the District of California, Civil Action No. 21-cv-03946-HDV-SK. December 6.

- 2022 – *Goleta Water District v. Slippery Rock Ranch, LLC*. Superior Court of the State of California. No. 1487005. March 18.
- 2022 – *Goleta Water District v. Slippery Rock Ranch, LLC*. Superior Court of the State of California. No. 1487005. March 12.
- 2021 – *Goleta Water District v. Slippery Rock Ranch, LLC*. Superior Court of the State of California. No. 1487005. August 31 - September 1.
- 2021 – *Goleta Water District v. Slippery Rock Ranch, LLC*. Superior Court of the State of California. No. 1487005. April 28.
- 2019 – *Goleta Water District v. Slippery Rock Ranch, LLC*. Superior Court of the State of California. No. 1487005. September 16 - 17.
- 2018 – *State of New York v. United Gas Corp., et al.* December 11 - 12.
- 2016 – *Waverley View Investors, LLC. vs. United States of America*. United States Court of Federal Claims. No. 15-371L. December 15.
- 2016 – *Samantha Hall vs. Conoco, Inc. et al.* United States District Court for the Western District of Oklahoma. No. 14-CV-670-HE. March 3.
- 2014 – *Jerilyn K. Allen et al. vs. ExxonMobil Corporation*. Circuit Court of the State of Maryland, County of Baltimore No. C-11-8536. April 4.
- 2011 – *State of New York vs. 913 Portion Road Realty Corp, et al.* Supreme Court of the State of New York. No. 26495-M. July 29.
- 2008 – *Jeff Alban et al. vs. ExxonMobil Corporation et al.* Circuit Court of the State of Maryland, County of Baltimore. No. 03-C-06-010932. February 6.

TESTIMONY-AT-TRIAL

- 2017 – *Waverley View Investors, LLC. vs. United States of America*. United States Court of Federal Claims. Case No. 15-371L. May 15.
- 2017 – *White Bear Lake Restoration Association, ex rel, State of Minnesota vs. Minnesota Department of Natural Resources and Thomas J. Landwehr in his Capacity as Commissioner of the Minnesota Department of Natural Resources*. State of Minnesota Second Judicial District Court, County of Ramsey. Case No. 62-CV-13-2414. March 23.
- 2017 – *Waverley View Investors, LLC. vs. United States of America*. United States Court of Federal Claims. Case No. 15-371L. January 18.