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Summary of Pine Valley Area Groundwater Studies

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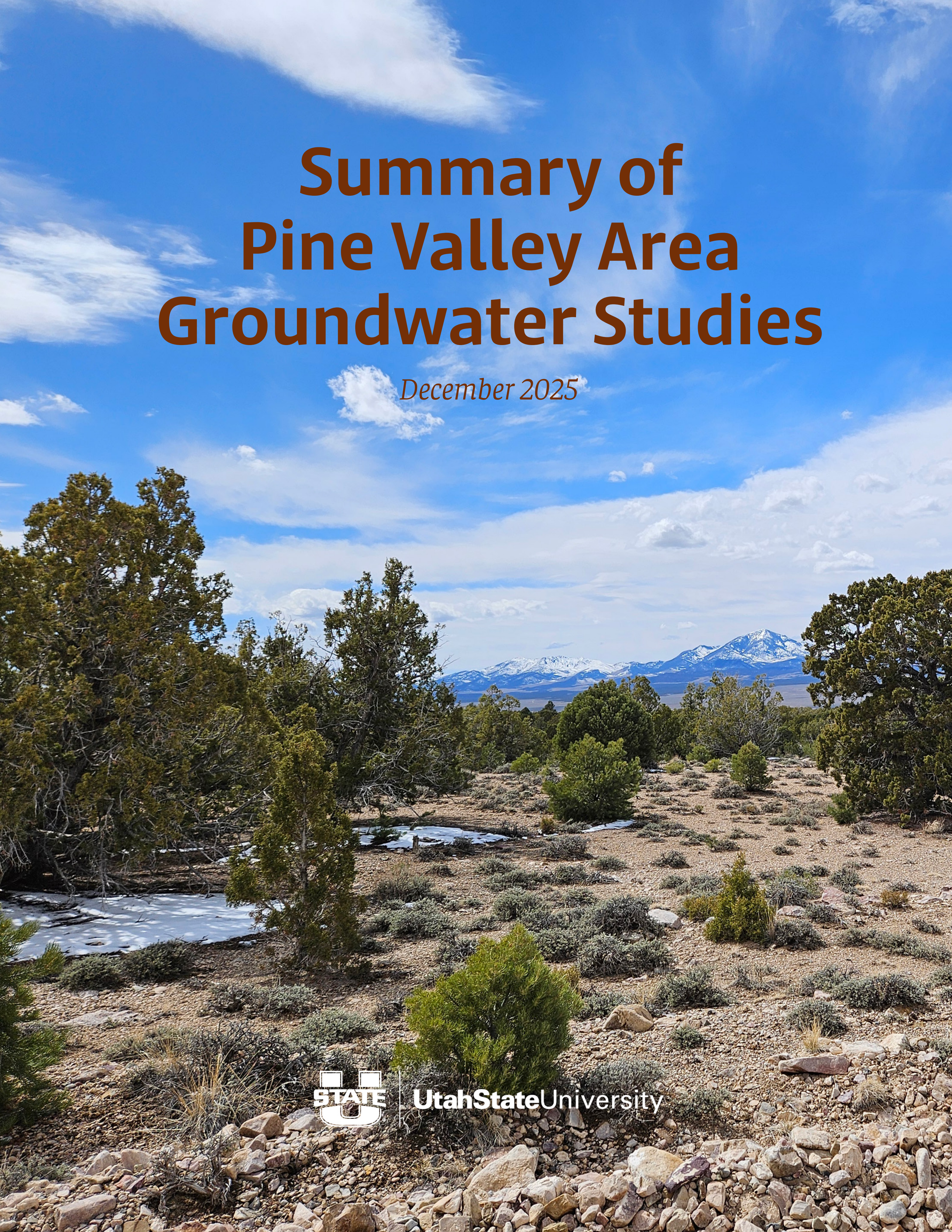

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Report Contents

Overview

Introduction

The Utah Division of Water Resources contracted with Utah State University to document key scientific and policy information related to the current water conflict between Iron and Beaver Counties over the development of the Pine Valley Water Supply Project (PVWSP). The proposed PVWSP would pump groundwater from Pine Valley in Beaver County and pipe it southeast to the Cedar City region of Iron County served by the Central Iron County Water Conservancy District (CICWCD). Numerous concerns about the project have been raised by Beaver County and other interested parties. A number of these concerns are related to different understandings or scientific uncertainties about the groundwater hydrology of Pine Valley.

This Groundwater Studies document summarizes the various scientific studies that explore and explain the hydrogeology of the Pine Valley area. It provides details about the datasets, scope, and methods used for each study, with a focus on groundwater recharge estimates that are critical to understanding water availability. The intent of this document is to describe and explain how and why the various studies arrived at different recharge estimates and hydrologic understanding.

To set the stage for understanding the summaries of groundwater studies related to Pine Valley, this Overview section starts by introducing some terminology and presenting a conceptualization of Pine Valley's water balance and groundwater recharge components. It then provides a timeline and overview of the studies that are reviewed in detail in the subsequent main section of this document.

Terminology and Geographic Context

The Pine Valley hydrographic area (HA) is located in a remote area of western Beaver and Millard Counties, Utah (Figure 1). It is understood to be connected to the Great Salt Lake (GSL) Desert regional groundwater flow system, which in turn is part of the larger Great Basin carbonate and alluvial aquifer system (GBCAAS) [1] . The GBCAAS encompasses a large 110,000 square mile area of western Utah and eastern Nevada in the Basin and Range Province. Because of rapid population growth and increasing groundwater demands in the region, the GBCAAS area was identified for study as part of the U.S. Geological Survey (USGS) National Water Census Initiative [1]. The GBCAAS includes 18 distinct regional groundwater flow systems delineated based on flow direction, inferred physical barriers, and significant discharge points [2]. These 18 flow systems are further divided into 165 HAs that were originally delineated for water management and scientific purposes. They typically represent individual watersheds that match topographic divides [1].

Some of the groundwater studies summarized in this document involved the entirety of the GBCAAS, but also provide results for the Pine Valley HA along with the other 164 HAs. Others were much smaller in scale, focusing just on the Pine Valley HA, or on both the Pine Valley and Wah Wah Valley HAs. Still others used study areas intermediate in size or included both large model areas combined with smaller focus areas (Figure 1). This document focuses on results generated for the Pine Valley HA but also provides context to be clear regarding the scale and geographic scope of the study that generated the Pine Valley results.

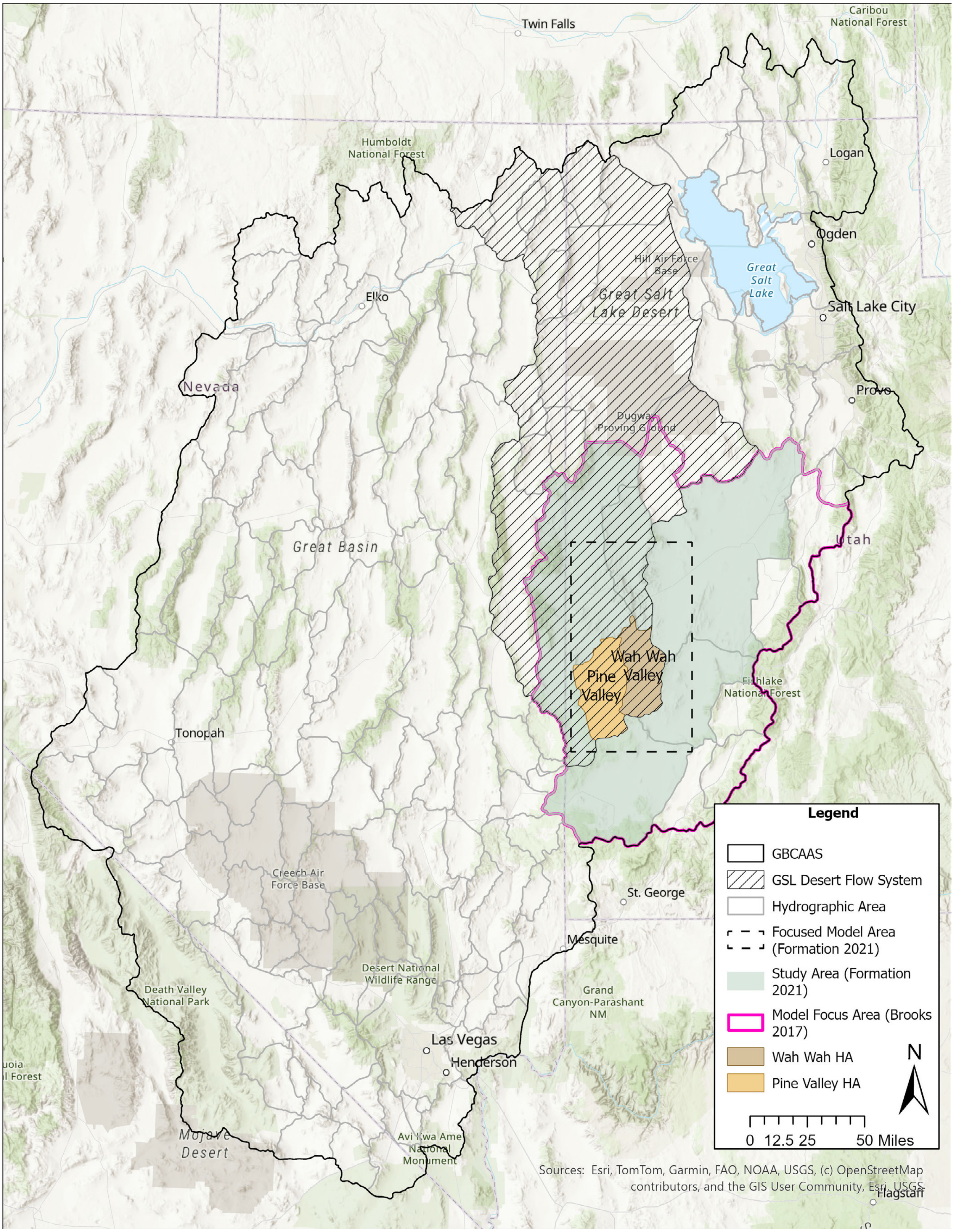


Figure 1. Location map of Pine Valley and study areas for various groundwater studies.

Terminology and Geographic Context *cont.*

In addition to a using variety of study area sizes, the groundwater studies summarized herein also use a variety of terms to describe different components of the Pine Valley aquifer (Figure 2). Throughout the remainder of this document, we use the simplified term "valley aquifer" to refer to the combined basin-fill and carbonate aquifer components that connect to the larger GSL Desert regional groundwater flow system. We use the simplified term "mountain aquifer" to refer to the mountain portion of the groundwater system that is understood to be at least partially disconnected from the regional groundwater system, and that commonly discharges as mountain springs and streams. It is important to note that the geologic layering and hydrogeology of Pine Valley is more complex than this simplified terminology reflects. However, these terms match the two main recharge processes discussed in the next section of this document and help to clarify which aquifer components different studies are developing estimates for. In this document, we also use many abbreviations and acronyms (see Table 1).

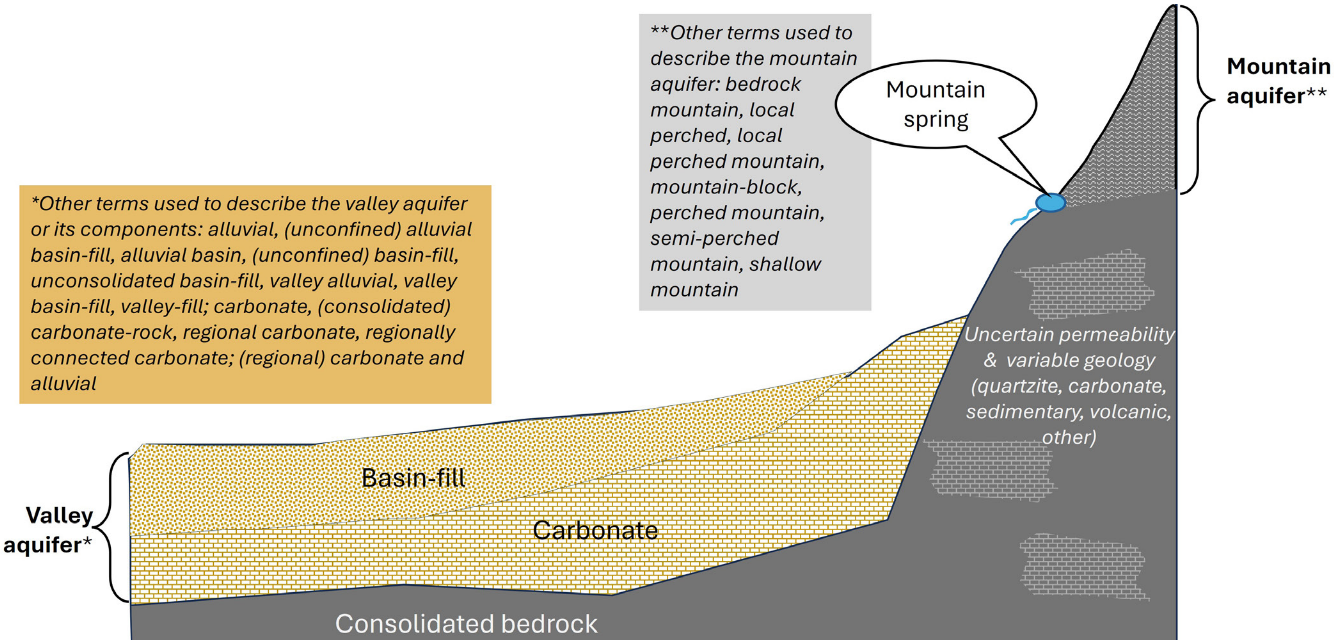


Figure 2.

Simplified Pine Valley aquifer diagram listing terminology used by the groundwater studies summarized in this document. Diagram is loosely based on Heilweil and Brooks (2011, Figure D-1)

Table 1. List of abbreviations and acronyms used in this document

Abbreviation	Term/Definition	Additional Description
AFY	Acre-feet per year	n/a
BCM	Basin characterization model	Water accounting method [3] used by Heilweil and Brooks 2011 [1]
BLM	U.S. Bureau of Land Management	n/a
CICWCD	Central Iron County Water Conservancy District	n/a
ET	Evapotranspiration	The process by which water moves from the land to the atmosphere by evaporation and transpiration by plants
ETg	Evapotranspiration of groundwater	Groundwater that discharges as evaporation or transpiration by plants
Formation	Formation Environmental	n/a
GBCAAS	Great Basin carbonate and alluvial aquifer system	110,000 square mile area of western Utah and eastern Nevada delineated for scientific study by USGS [1]
GBCAAS 1.0	First iteration of USGS GBCAAS groundwater model	Numerical groundwater flow model developed by Brooks et al. 2014 [4]. Uses MODFLOW-2005 software.
GBCAAS 3.0	Third iteration of USGS GBCAAS groundwater model	Numerical groundwater flow model developed by Brooks 2017 [5]. Uses MODFLOW-LFR software.
GBCAAS-PV	Revision of GBCAAS 3.0 groundwater model	Numerical groundwater flow model developed by Formation Environmental [6] to assess environmental impacts of the Pine Valley Water Supply Project.
GDA	Groundwater discharge area	An area of phreatophytic (water-loving) vegetation where groundwater discharges and evapotranspires
GPM	Gallons per minute	n/a
GSL	Great Salt Lake	n/a
HA	Hydrographic Area	Geographic area delineated for water management and scientific purposes; typically represents an individual watershed matching topographic divides [2]
Isohyet	Line of equal precipitation	n/a
KAFY	Thousand acre-feet per year	n/a

Table 1. List of abbreviations and acronyms used in this document cont.

Abbreviation	Term/Definition	Additional Description
Landsat	An earth-observing satellite program managed by USGS and the National Aeronautics and Space Administration	Landsat satellites collect remote sensing imagery of the entire earth approximately every 1-2 weeks. The image scenes for a given time and location can be downloaded for analysis.
MODFLOW-2005	n/a	A USGS numerical groundwater flow modeling software package
MODFLOW-LGR	MODFLOW-Local Grid Refinement	An enhanced version of MODFLOW-2005 that allows the use of a higher-resolution "child model" within a coarser resolution/larger-area "parent model"
Mountain aquifer	The aquifer present in the mountain portion of the Pine Valley HA	This aquifer is understood to be at least partially disconnected from the regional groundwater system and commonly discharges as mountain springs and streams.
NEPA	National Environmental Policy Act	n/a
NGTs	Noble gas temperatures	Used to help determine the origin of groundwater recharge. Groundwater that recharged in a cooler mountain environment will have a lower NGT than groundwater that recharged in a warmer valley environment.
NREL	National Radiation Energy Laboratory	n/a
NWIS	National Water Information System	U.S. Geological Survey web-based water data service for accessing streamflow, groundwater (water levels in wells), water quality, and other water-related data [7]
P	Precipitation	n/a
PET	Potential evapotranspiration	The greatest amount of evapotranspiration possible assuming no limitations on water availability
Pine Valley	Pine Valley Hydrographic Area	Unless otherwise specified, used to describe the entire hydrographic area, including the valley and mountain areas to the basin divide.
PRISM	Parameter-Elevation Regressions on Independent Slopes Model	Gridded precipitation and climate information developed as described in Daly et al. 2008 [8]
PVWSP	Pine Valley Water Supply Project	Proposed project to pump Pine Valley groundwater and pipe it to the Cedar City area
R	Groundwater recharge	Water that recharges a groundwater aquifer
Transmissivity	Rate at which groundwater moves through an aquifer	The product of hydraulic conductivity and saturated aquifer thickness

Table 1. List of abbreviations and acronyms used in this document cont.

Abbreviation	Term/Definition	Additional Description
USGS	U.S. Geological Survey	n/a
Valley aquifer	The combined basin-fill and carbonate aquifer components present in the flat valley portion of the Pine Valley HA	This aquifer is understood to be connected to the larger GSL Desert regional groundwater flow system

Pine Valley Water Balance and Groundwater Recharge Conceptualization

Pine Valley is a closed basin with no streams or rivers flowing out of it. Consequently, it is challenging to measure outflows from the basin to help refine groundwater recharge estimates. In addition, Pine Valley groundwater development to date has been minimal, which limits the availability of data on the area's aquifer and groundwater characteristics. Therefore, despite the existence of a number of scientific studies, considerable uncertainties about Pine Valley's hydrology remain.

When considering the different estimates of groundwater recharge in Pine Valley, it is helpful to consider a conceptual illustration of the system (Figure 3). There are two distinct, but related, components to the valley aquifer recharge process in Pine Valley: direct valley recharge and mountain recharge.

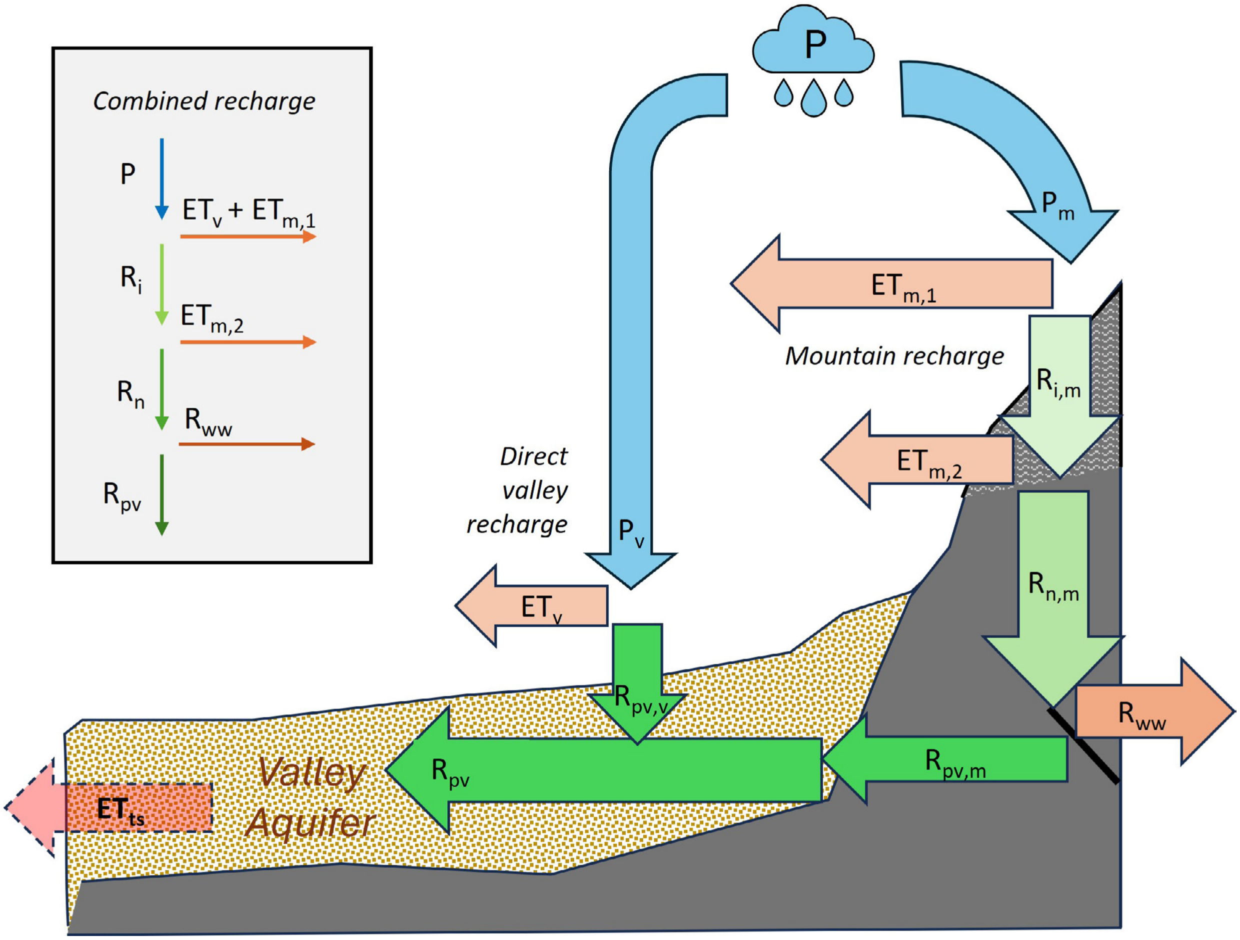


Figure 3. Conceptual illustration of inflows and outflows in Pine Valley's valley aquifer. Loosely based on water budget components described in Stephens 1976 [9].

Pine Valley Water Balance and Groundwater Recharge Conceptualization *cont.*

The source of direct valley recharge is precipitation that falls in the valley (P_v). Most of this precipitation evaporates or is transpired by plants (ET_v) before what remains recharges the valley aquifer ($R_{pv,v}$):

$$R_{(pv,v)}=P_v-ET_v$$

The mountain recharge process is more complicated. Most of the precipitation that falls in the mountains (P_m) evaporates or is transpired by plants ($ET_{m,1}$) before it initially recharges the groundwater ($R_{i,m}$):

$$R_{i,m}=(P_m-ET_{m,1})$$

Some of this initial mountain recharge then discharges as perched mountain springs and streams and evapotranspires ($ET_{m,2}$); the remaining recharge is the net mountain recharge ($R_{n,m}$):

$$R_{n,m}=R_{i,m}-ET_{m,2}$$

Due to underlying rock layers that dip eastward in the Wah Wah Mountains, some of the $R_{n,m}$ is assumed to flow subsurface into Wah Wah Valley's groundwater (R_{ww}). The remainder recharges Pine Valley's valley aquifer ($R_{pv,m}$):

$$R_{pv,m}=R_{n,m}-R_{ww}$$

The total Pine Valley valley recharge (R_{pv}) is the sum of the direct valley recharge ($R_{pv,v}$) and this net mountain recharge ($R_{pv,m}$). The Rpv groundwater is believed to flow subsurface out of Pine Valley toward the north where it leaves the system as ET in Tule and Sevier Valleys (ET_{ts}), so at present:

$$R_{pv}= R_{pv,m}+R_{pv,v}=ET_{ts}$$

The Rpv groundwater or ET_{ts} is the water that could be withdrawn from the valley aquifer without impacting storage volumes once the aquifer reaches a new equilibrium.

In terms of combined mountain and valley recharge, the net groundwater recharge (R_n) includes the valley aquifer groundwater (R_{pv}) plus the portion assumed to flow subsurface into Wah Wah Valley's groundwater:

$$R_n=R_{pv}+R_{ww}$$

Total initial recharge (R_i) is often reported as total groundwater recharge. It includes net total groundwater recharge plus mountain groundwater that evapotranspires as mountain spring and stream discharge ($ET_{m,2}$):

$$R_i=R_n+ET_{m,2}$$

The combined recharge all originates from total precipitation (P) which includes the precipitation that falls in both the valley (P_v) and mountains (P_m):

$$P=P_m+P_v=R_i+ET_{m,1}+ET_v$$

For reference, a complete list of these terms and their definitions is provided in Table 2.

Table 2. List of groundwater recharge terms/abbreviations

Process Component	Term	Definition
Combined Recharge	P	Total precipitation
	R_i	Total groundwater recharge/total initial recharge
	R_n	Net groundwater recharge
	R_{pv}	Recharge to valley aquifer of Pine Valley
	ET_{ts}	Subsurface interbasin discharge of Pine Valley groundwater out of Pine Valley assumed to evapotranspire in Tule and Sevier Valleys
Mountain Recharge	P_m	Mountain precipitation
	$ET_{m,1}$	Initial evapotranspiration of mountain precipitation
	$R_{i,m}$	Initial mountain recharge
	$ET_{m,2}$	Portion of initial mountain recharge that discharges as mountain springs and streams and evapotranspires
	$R_{n,m}$	Net mountain recharge
	R_{ww}	Subsurface discharge to Wah Wah Valley
	$R_{pv,m}$	Portion of recharge to valley aquifer that originates as mountain recharge
Valley Recharge	P_v	Valley precipitation
	ET_v	Evapotranspiration of valley precipitation
	$R_{pv,v}$	Portion of recharge to valley aquifer that originates as direct valley recharge

Timeline and Overview of Studies

Various scientific studies have investigated the groundwater hydrology of the Great Basin area in general, and the Pine Valley HA in particular. The timing and relationships among key studies summarized in this document are illustrated in Figure 4. As evident in the key results summarized in Table 3, the recharge estimates reported in the different studies are highly variable. This variability is associated with differences in the geographic scope, methodology, data sources and time frames, and assumptions made in each study. The studies also vary in which specific recharge component (R_i, R_n, or R_{pv}, Figure 3) is estimated. The Summaries of Studies section of this document provides more detailed explanations of each study's scope, methods, and data sources.

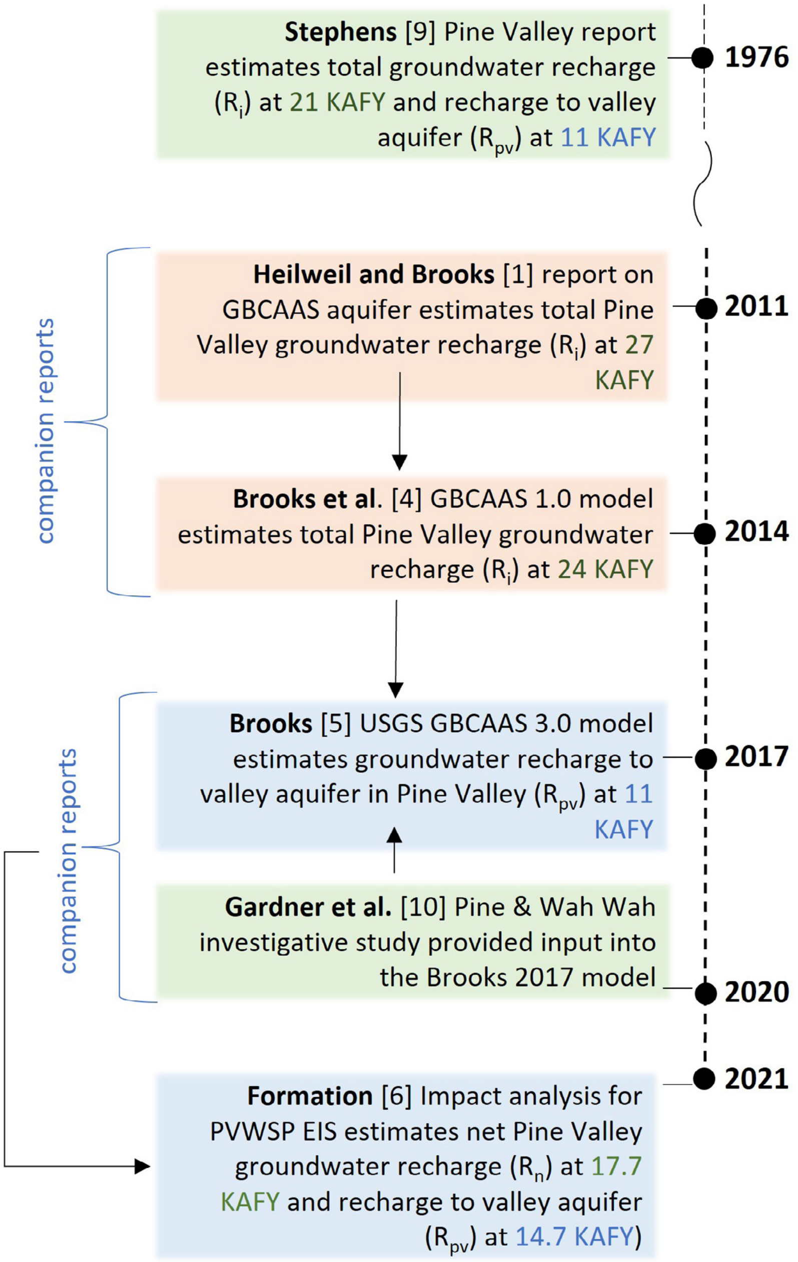


Figure 4. Timeline of scientific studies of groundwater hydrology of Pine Valley and surrounding regions. Arrows indicate instances where one study directly informed another. Colors indicate primary geographic extent of study (Green = Pine and Wah Wah Valleys; Peach = GBCAAS; Blue = Intermediate size area including Pine, Wah Wah, and additional HAS).

Table 3. Overview of scientific studies and their estimated Pine Valley recharge and precipitation values.

STUDY	FOCUS AREA	TYPE OF STUDY	RECHARGE ESTIMATION METHOD	AVERAGE ANNUAL RECHARGE ESTIMATE(S) IN KAFY	PRECIPITATION ESTIMATE (IN KAFY) AND METHODS
Stephens 1976 [9]	Pine Valley	Conceptual/ empirical	Empirical method that applies distinct recharge percentages to mapped precipitation and geology zones	**21** (R_i), reported in Table 4 **11** (R_{pv}), reported on p.21.	**410** U.S. Weather Bureau isohyets for 1931-1960
Heilweil and Brooks 2011 [1]	Entire GBCAAS	Conceptual/ regional water balance accounting model	Basin Characterization Model w/ spatial data and monthly climate data inputs; monthly results averaged over 67-year analysis period	**27** (R_i), reported in Table A4-1	**472** Gridded, resampled PRISM data for 1971-2000
Brooks et al. 2014 [4]	Entire GBCAAS	Steady-state regional numerical groundwater flow model	Flow simulation calibrated to provide reasonable match to observed water levels and discharge rates	**24** (R_i), reported in Table A3-2	n/a
Brooks 2017 [5]	Southern GSL Desert and Sevier Lake systems; model includes entire GBCAAS	Local updates to regional numerical groundwater flow model; includes both steady-state and transient simulations	Steady-state flow simulation using locally-updated calibration data	**11** (R_{pv}), reported in Table 8	n/a
Gardner et al. 2020 [10]	Pine and Wah Wah Valleys	Investigative data collection and analysis	n/a. Research for this study provided input into the Brooks 2017 modeling estimates	n/a	**510** Gridded PRISM data for 1981-2010
Formation 2021 [6]	Pine and Wah Wah Valleys and surrounding HAs; model includes entire GBCAAS	Impact assessment/ investigative data compilation and analysis/ numerical groundwater flow model with steady-state calibration and transient predictive simulations	Subtraction of average evapotranspiration estimate from average precipitation estimate	**17.7** (R_n), reported in Table 3-18 **14.7** (R_{pv}), reported in Table 3-19	**388** Average of 6 weather stations in/near Pine Valley with variable periods of record

Summaries of Studies

The following sections of this report provide more detailed information about each scientific study that explores Pine Valley's hydrogeology. The studies are presented in chronological order. We begin each section with a one-page graphical summary and then discuss each study's purpose, geographic scope, methods, and key results in more detail. Additional details on methods are provided in Appendix A.

We often refer to specific tables and figures and pages of the studies being summarized. When we do this, we include the study author in parentheses with a colon followed by the page number, table number, or figure number, e.g., (Stephens:Table X). This is intended to distinguish tables and figures from the original source from our new tables and figures developed for this Summary of Groundwater Studies document.

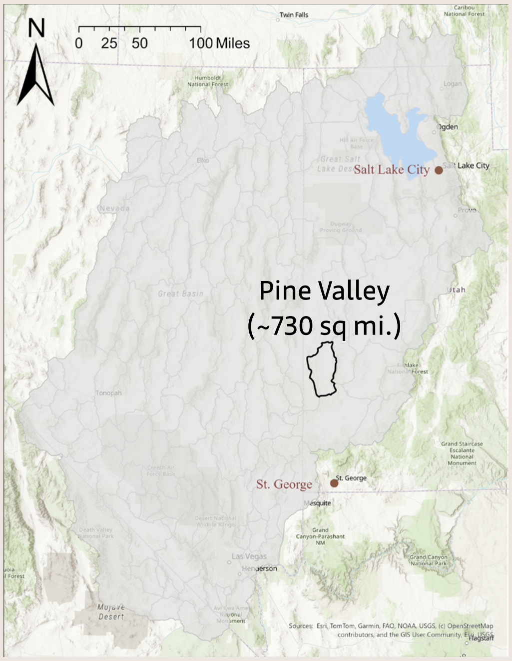
Stephens 1976 *quick look*

Citations and Affiliations

J. Stephens, "Hydrologic Reconnaissance of the Pine Valley Drainage Basin, Millard, Beaver, and Iron Counties, Utah," State of Utah Department of Natural Resources, Technical Publication No. 51, 1976. [Online]. Available: https://pubs.er.usgs.gov/publication/70042823

The Stephens (1976) study was authored by Jerry C. Stephens, a hydrologist with the USGS. The study was prepared in cooperation with the Utah Department of Natural Resources, Division of Water Rights.

Primary Study Area



Sources: Esri, TomTom, Garmin, FAO, NOAA, USGS, (c) OpenStreetMap contributors, and the GIS User Community

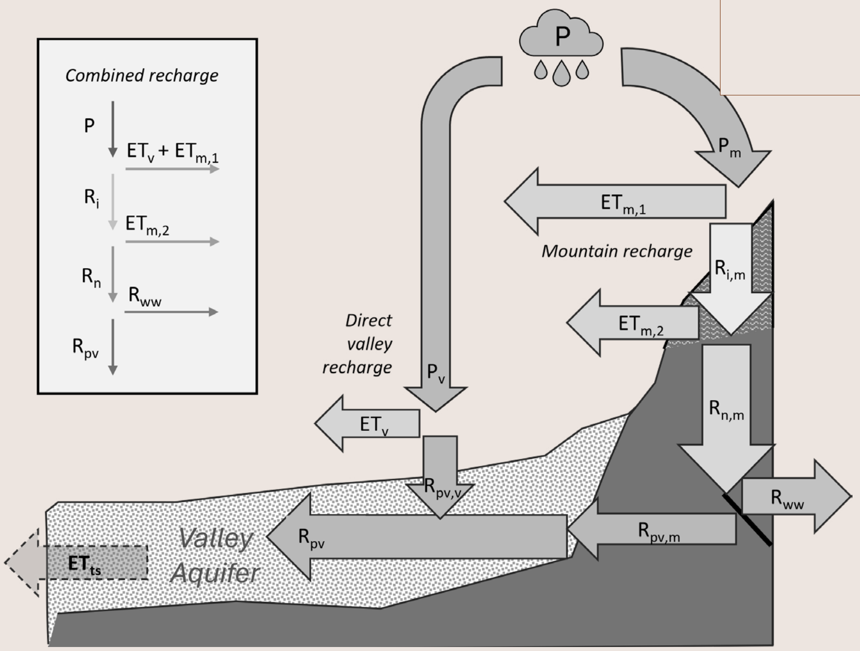
Study Type

Conceptual,
Empirical

Key Results

Component	Estimation Method	Estimate (in KAFY)	Description
Precipitation	Based on 1931-1960 US Weather Bureau isohyets/ spatial averaging	410 (P)	Total precipitation (=$P_m + P_v$)
Recharge	Empirical method that applies distinct recharge percentages to mapped precipitation and geology zones	21 (R_i)	Total groundwater recharge/total initial recharge
		14 (R_n)	Net groundwater recharge
		11 (R_{pv})	Recharge to valley aquifer of Pine Valley

Key to Recharge Components



Stephens 1976 *summary*

Scope/Geographic Context

The Stephens (1976) study focuses on Pine Valley Hydrologic Area (Figure 1), but also considers a portion of the Wah Wah Valley HA with groundwater linkages to Pine Valley. It lists the total area of the Pine Valley drainage basin as 466,000 acres (728 square miles; Stephens:Table 4). The report presents general information on the climate, geography, vegetation, geology, and hydrology of Pine Valley. It assesses groundwater recharge, storage, water quality, and availability of supply for development.

Purpose

The Stephens (1976) study is one of many studies completed by USGS in cooperation with the Utah Division of Water Rights. Its purpose is to provide an understanding of the area's hydrology, evaluate water development potential, and recommend additional studies that would enhance understanding of the area's hydrology.

Methods

Precipitation

Stephens (1976) cites several precipitation data sources. He reports the annual average for the basin as 10.6 inches (Stephens:5) based on U.S Weather Bureau isohyets representing 1931-1960 "normal" precipitation. This precipitation data is also the source of precipitation estimates presented for specific locations on ephemeral streams (Stephens:Table 3), and for estimates presented for different precipitation zones/rock types (Stephens:Table 4). The study lists overall average annual Pine Valley precipitation volume as 410,000 AF (Stephens:Table 4). Stephens (1976) also presents monthly precipitation and temperature data for the Desert Experimental Range weather station located in the northern valley area of the Pine Valley HA. These data are provided as averages for the January 1950-December 1973 time period (Stephens:Table 1) and illustrate that average precipitation in lower-elevation valley areas is significantly less than in higher-elevation mountain areas.

Evapotranspiration

Stephens (1976) describes the types and extent of groundwater-dependent (phreatophytic) vegetation present along the springs and creeks in the mountain areas of Pine Valley. The study states that the estimated total area of these vegetation types is 5,500 acres and assumes a 1 ft/year average groundwater consumption rate to generate an ETg estimate of 5,500 AFY (Stephens:17). Specific methods used to generate the vegetated area estimate are not presented. Areas of "significant evapotranspiration by phreatophytes" are shown on a map figure that accompanies the report (Stephens:Plate 1).

Spring/Stream Discharge

Channel geometry measurements were used to generate runoff estimates (Stephens:Table 3) for four locations along Pine Valley Wash, the north-flowing ephemeral stream located at the bottom of the valley. The largest of these is 1,200 AFY. The values are presented as estimates rather than actual measurements. The same channel geometry-based approach was used to estimate discharge at four streams (Turkey Wash and Pine Grove, Indian, and Sheep Creeks) in November 1973; flow estimates ranged from 0.1 to 1.0 cfs and totaled 1.6 cfs (Stephens:16). A portion of this total (0.1 cfs) was estimated to be from snowmelt rather than groundwater discharge, and 10% of the remaining 1.5 cfs was estimated to infiltrate back into the valley aquifer. No details or citations are provided to explain these discharge values and we therefore assume they are estimates rather than actual discharge

Methods *cont.*

measurements. The resulting 1.3 cfs equals an estimate of 940 AFY of groundwater discharged via seepage to mountain streams.

The study estimates that annual discharge from springs is 650 AFY (Stephens:15). This estimate is based on an assumption of average continuous flow of 5 gallons per minute (GPM) per spring for each of 80 springs mapped on USGS topographic maps. Stephens (1976) presents a mix of measured and estimated discharge data from 20 springs that were visited as part of the study and/or previous to the study (Stephens:Table 7). Most of the 20 springs are developed and used for stock watering. For springs where information is presented for multiple dates, discharge rates varied significantly.

Groundwater Levels

Reported water levels at five wells are included in the report (Stephens:Table 5). Results generally show north-moving groundwater, although one historical measurement at a single, now-defunct, well suggested flow towards the south.

Geochemistry

The report (Stephens:Tables 7, 8, 9) presents a mix of water temperature, specific conductance, and dissolved minerals data for several springs, creeks, wells, and Central Pine Reservoir (a small ~1 acre impoundment on Pine Valley Wash). Results are summarized in a map (Stephens:Plate 1).

Other Data

Driller's logs of three wells are provided (Stephens:Table 6).

Water Balance Estimation

This report did not involve analytical or mathematical groundwater flow modeling. The authors reviewed available data and collected additional data on geomorphology, geology, vegetation, and hydrology during field visits in October 1972 and June and November 1973.

Stephens (1976) calculated initial total Pine Valley groundwater recharge (Ri) by dividing the basin into subareas with comparable geology/precipitation and then applying empirical recharge percentages to the precipitation volume for the subarea. This methodology (Eakin et al. 1951[11], Hood and Waddell 1968 [12], Maxey and Eakin 1949 [13]) was commonly used in Great Basin groundwater studies during this time period. Stephens (1976) provides the individual subarea calculations in a table (Stephens:Table 4). The table includes a group of subareas assumed to have underlying rock strata that dip eastward and therefore contribute groundwater to the Wah Wah Valley HA as well as the Pine Valley HA. Total recharge calculated for this Wah Wah group was then split, with 60% assumed to drain subsurface to Wah Wah Valley (R_{ww}) and 40% to Pine Valley.

The Stephens (1976) study then estimated annual recharge to Pine Valley's valley aquifer (R_{pv}) by subtracting estimates of evapotranspiration, mountain spring/stream discharge, and subsurface discharge to Wah Wah Valley from the initial total recharge (R_i) estimate.

Key Results

Water Balance & Recharge Estimates

Estimates of the various water balance components from the Stephens (1976) study are summarized in our Table 4 and our Figure 5. The study estimates total Pine Valley recharge (R_i) at 21 KAFY and annual recharge to the valley aquifer (R_{pv}) at 11 KAFY (Stephens:17).

Table 4. Stephens (1976) water balance and recharge estimates for Pine Valley.

Component	Estimated Value	Description/Method
Total Precipitation (P)	410 KAFY	Based on 1931-1960 US Weather Bureau isohyets/spatial averaging
Total Groundwater Recharge (R_i)	21 KAFY	About 5% of precipitation based on methods from Eakin et al. 1951 [11]and Hood & Waddell 1968 [12].
Portion of initial mountain recharge that discharges as mountain springs and streams and evapotranspires ($ET_{m,2}$)	7 KAFY	Sum (rounded) of subcomponents listed below: 5,500 AFY + 650 AFY + 940 AFY
Mountain evapotranspiration	5,500 AFY	Assumed 1 ft/year average groundwater consumption rate for 5.5 KA of mapped phreatophytic vegetation
Discharge to mountain springs	650 AFY	Assumption of average continuous flow of 5 GPM per spring for each of 80 springs
Discharge via seepage to streams	940 AFY	Select streamflow measurements in Nov. 1973 and estimates of % snowmelt, % re-infiltration
Discharge by wells	5 AFY (“insignificant”)	
Net groundwater recharge (R_n)	14 KAFY	Estimate of groundwater that discharges subsurface. Calculated by subtracting $ET_{m,2}$ (7 KAFY) from R_i (21 KAFY). Includes 3 KAFY assumed to flow subsurface to Wah Wah Valley.
Subsurface discharge to Wah Wah Valley (R_{ww})	3 KAFY	Assumption of groundwater divide based on geologic understanding. Assumption that 60% of mountain recharge in area with groundwater divide drains to Wah Wah Valley HA.
Recharge to valley aquifer of Pine Valley (R_{pv})	11 KAFY	R_n (14 KAFY) minus R_{ww} (3 KAFY)
Subsurface interbasin discharge out of Pine Valley (ET_{ts})	11 KAFY	Assumption of equilibrium
Subsurface interbasin inflows to Pine Valley	Not addressed	
Change in groundwater storage	0	Assumption of equilibrium given minimal groundwater development

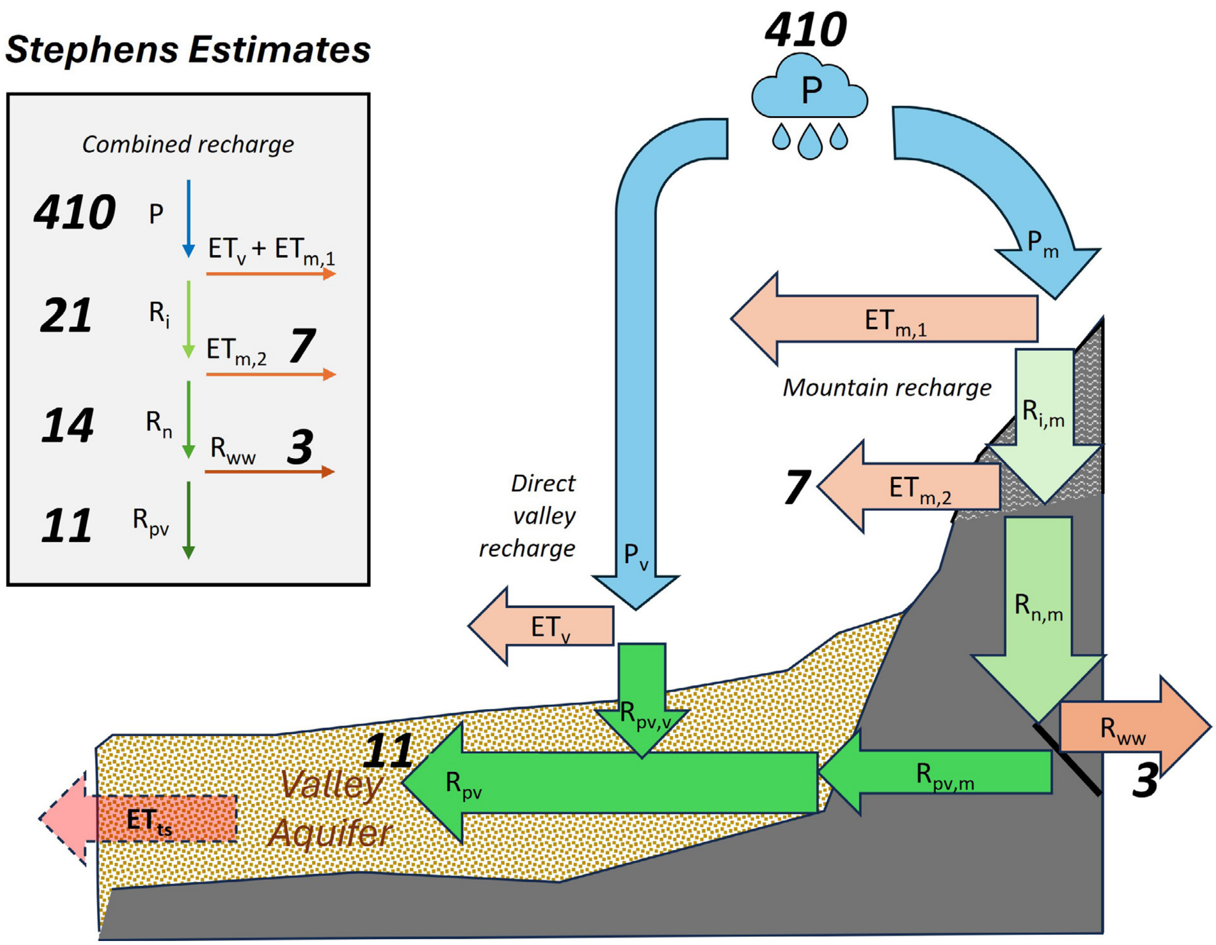


Figure 5. Values estimated by Stephens (1976) for Pine Valley water balance components, in thousands of acre feet per year (KAFY).

Key Results *cont.*

Water Balance Assumptions

- Mountain evapotranspiration estimate assumes a 1 ft/year average groundwater consumption rate. No citation or supporting data are provided for this assumption.
- Total spring discharge estimate is based on an assumption of average continuous flow of 5 GPM per spring for each of 80 springs. The spring discharge estimates/measurements presented (Stephens:Table 7) range from 0.15 to 60 GPM and are temporally variable.
- 3,000 AFY of groundwater is assumed to discharge subsurface toward east into Wah Wah Valley. This assumption is based on a geologic understanding that the Wah Wah Mountains that form the eastern boundary of Pine Valley are underlain by rock strata that dip eastward. The study includes the specific Maxey-Eakin based estimates for the individual subareas within this Wah Wah groundwater basin portion of Pine Valley, which total 5,000 AFY (Stephens:Table 4). However, no explanation is provided for how it was determined that 3,000 AFY of that total drains to Wah Wah Valley.

Findings

The study concludes that additional water supplies could be developed in Pine Valley. Spring flow discharge could be captured, collected, and diverted, and wells could be constructed. The study predicts that the main impact of development and consumptive use of Pine Valley groundwater would be to reduce subsurface discharge out of the basin.

Study Recommendations

The study recommends collecting more data to better understand the basin's hydrology, specifically:

- Drilling wells in southern portions of the valley and collecting water level, water quality, and geologic data
- Drilling in the mountains of the southern Needle Range to identify and map perched groundwater zones
- Investigating water quality variability

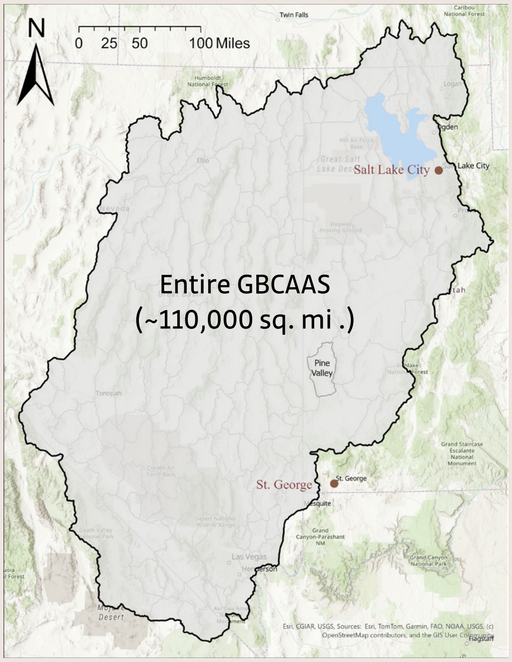
Heilweil and Brooks 2011 *quick look*

Citations and Affiliations

V. M. Heilweil and L. E. Brooks, "Conceptual Model of the Great Basin Carbonate and Alluvial Aquifer System," U.S. Geological Survey Scientific Investigations Report 2010–5193, 2011. [Online]. Available: https://pubs.usgs.gov/sir/2010/5193/

The Heilweil and Brooks (2011) study was authored by Victor Heilweil and Lynette Brooks of the U.S. Geological Survey (USGS). It was conducted as part of the USGS National Water Census Initiative. The area was of interest because of rapid population growth and increasing groundwater demands in the region.

Primary Study Area



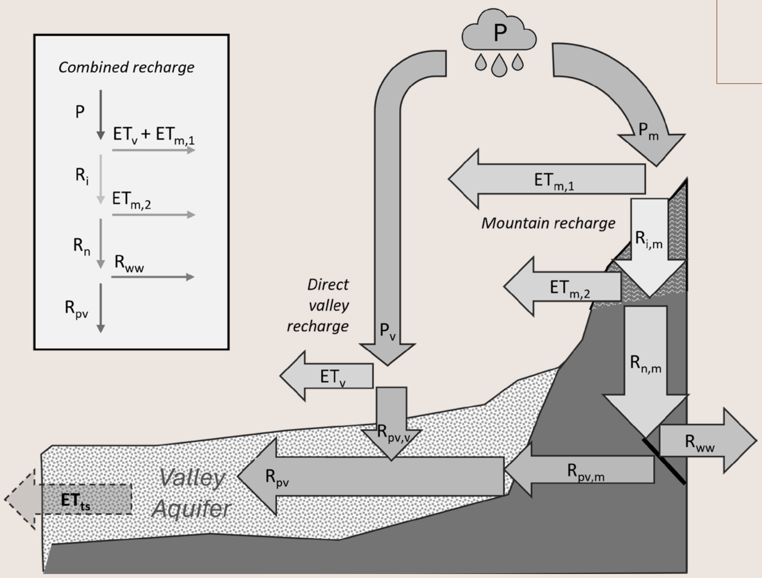
Study Type

Conceptual; regional water balance accounting model

Key Results

Component	Estimation Method	Estimate (in KAFY)	Description
Precipitation	Gridded, resampled PRISM data for 19712000	472 (P)	Total precipitation (=Pm + Pv)
Recharge	Basin Characterization Model w/ spatial data and monthly climate data inputs; monthly results averaged over 67-year analysis period	27 (Ri)	Total groundwater recharge/total initial recharge

Key to Recharge Components



Heilweil and Brooks 2011 *summary*

Scope/Geographic Context

This report builds on a prior Regional Aquifer Systems Analysis effort completed during the 1980-1990s time frame by the USGS. It evaluates the Great Basin carbonate and alluvial aquifer system (GBCAAS) area which comprises 110,000 square miles of western Utah and eastern Nevada (Figure 1). The study evaluates groundwater budgets for all hydrographic areas (HAs) in the GBCAAS based on summaries of previous studies as well as recharge calculations generated using a Basin Characterization Model (BCM) water accounting method. It also describes a three-dimensional hydrogeologic framework for the GBCAAS that identifies distinct hydrogeologic units and develops a map of groundwater levels and gradients.

Purpose

This study was completed to better assess availability of groundwater in the GBCAAS region. It expands and adjusts the study area of previous assessments. It also incorporates more recent data and findings and utilizes newer digital data sets and tools.

Methods

Precipitation

The Heilweil and Brooks (2011) study used PRISM gridded precipitation data. PRISM (Parameter-elevation Regressions on Independent Slopes Model) is a computer algorithm that uses available weather station data and gridded elevation data to model precipitation for individual pixels within a topographic grid [8]. The results are available as spatially-robust, GIS-compatible data products that can be used to assess specific areas of interest. Specifically, the Heilweil and Brooks (2011) study used 4 km resolution gridded PRISM data resampled to a 270 meter grid. The study presents a map (Heilweil & Brooks:Fig D-2) of annual precipitation bands for all the HAs in the GBCAAS, including Pine Valley, averaged over the 1940-2006 time frame. This map shows most of Pine Valley receiving 5-15" of precipitation per year, with the highest parts of the mountains getting 15-20" per year. Monthly precipitation estimates over this same time frame were used in the study's Basin Characterization Model (BCM.) The study lists PRISM-based mean annual precipitation estimates for each HA over the 1971-2000 time period, with the Pine Valley HA value shown as 12 inches per year (Heilweil & Brooks:Table A2-1). Using a Pine Valley area of 472,200 acres, this equates to 472 KAFY.

Modeling

The Heilweil and Brooks (2011) study used a large-scale BCM approach [1], [3] to develop annual groundwater recharge and runoff estimates for the entire GBCAAS and for the individual HAs within the GBCAAS. The BCM is a distributed-parameter water balance accounting model that uses spatial data sets (soils, vegetation, geology, etc.) and monthly climate data to calculate recharge and runoff for individual grid cells. The spatial resolution of all Heilweil and Brooks (2011) BCM input files were based on a digital elevation model with a 270-m resolution grid, and output calculations were made on that same grid size. This study's BCM runs using Fortran code and generates monthly outputs. Output data are summarized by individual HAs and averaged over the 1940-2006 time period to generate annual recharge estimates for each HA.

Heilweil and Brooks (2011) emphasize that it is important to understand that the recharge estimates the BCM model application generates for each HA represent total recharge, including groundwater lost via mountain spring/stream discharge. Therefore, their recharge estimates do not necessarily reflect the valley aquifer groundwater that is physically available for wells or pipelines.

The BCM methods used by Heilweil and Brooks (2011) are briefly summarized below. Detailed methods are described in the study document (Heilweil & Brooks: Chapter D and Appendix 3).

Methods *cont.*

Spatial Input Data

The Heilweil and Brooks (2011) study compiled various spatial data sets into a GIS for use in the BCM. These included:

- A 30-m digital elevation model [14] resampled to a coarser 270-m grid
- State Soil Geographic Database soil information (STATSGO) [15] including porosity, thickness, and sand/silt/clay percentages
- Geologic unit information from published state geologic maps

Additional spatial input data were generated from the above data sets as follows:

- Gridded values of total soil-water storage capacity were calculated by multiplying STATSGO thickness by porosity.
- Empirical equations [16] were used to calculate soil water content and wilting point values based on STATSGO sand and clay percentage information.
- Saturated hydraulic conductivity estimates were initially generated for each geologic unit based on expert opinion, literature review, aquifer test results, and infiltration experiments. The resulting values were refined during model calibration and are presented in the report (Heilweil & Brooks:Table A3-1).

Temporal Input Data

Heilweil and Brooks' BCM model application used PRISM monthly estimates (4-km grid resampled to 270-m) of precipitation and minimum and maximum air temperature as core data inputs. This input data set encompasses the 1940-2006 time period.

For each grid cell, monthly values of potential evapotranspiration (PET) were estimated using the Priestley-Taylor equation [17]. PET equation inputs included the PRISM air temperature data, USGS National Gap Analysis land cover information [18], and outputs from a solar radiation/topographic shading model based on DEM topography and National Radiation Energy Laboratory (NREL) average monthly cloudiness data.

Snow accumulation estimates were determined using Lundquist and Flint (2006) [19] energy and mass balance calculations.

Water Balance Calculations

The Heilweil and Brooks (2011) BCM calculates runoff and recharge at a monthly timestep for each grid cell. It computes available water based on precipitation, snowmelt, PET, antecedent soil water, and snow accumulation. The available water is then partitioned into runoff or recharge based on soil-water storage capacity and hydraulic conductivity characteristics.

Basin Characterization Model (BCM) Calibration

Hydraulic conductivity input information was adjusted based on a comparison of BCM-predicted runoff with streamflow gage data in 44 HAs. No gaged streamflow data were available for Pine Valley. The adjustments to hydraulic conductivity values for each geologic unit were made to optimize the match between gaged runoff estimates and BCM estimates for the overall GBCAAS area.

Solar radiation input data were compared to available NREL cloudiness data and corrected as needed. BCM-calculated PET values were compared to estimates based on measured data for California and Arizona, and based on Nevada meteorological data. These comparisons of PET values generally matched well and no adjustments were made to the BCM values.

Methods *cont.*

Remote-sensing based snowcover extent information (MODIS) [20] was used to evaluate the BCM-generated snowmelt and snow accumulation values. Based on these comparisons, an adjustment was made to the temperature threshold used in the BCM to define precipitation as snow rather than rain.

The Heilweil and Brooks (2011) study compared their calculated BCM recharge values with previously-estimated groundwater discharge information. Large discrepancies were found in some HAs, and in these instances the BCM results were adjusted by a multiplication factor (Heilweil & Brooks: 86; Fig D-8) to provide a better match. No adjustments were made to BCM results for Pine Valley HA or any HAs adjacent to Pine Valley. The groundwater discharge information used for comparison was compiled primarily based on previous estimates of evapotranspiration from groundwater discharge areas (ET_g) and measured/estimated discharge information from mountain streams and springs.

Key Results

Water Balance & Recharge Estimates

The estimates of precipitation and groundwater recharge reported in the Heilweil and Brooks (2011) study for the Pine Valley HA are summarized below in our Table 5 and our Figure 6. No other individual water budget components for specific HAs are presented in the study.

Assumptions and Limitations

Several limitations are noted in the Heilweil and Brooks (2011) study:

- Sensitivity analysis results suggest that the Heilweil and Brooks (2011) recharge estimates have uncertainty of ± 50%.
- The BCM model assumes recharge occurs within a monthly time step but groundwater travel time may be much longer in some places.
- Geologic maps used to determine hydraulic conductivity are low resolution (1:500,000) and may not represent local conditions well.

Table 5. Heilweil and Brooks (2011) water balance and recharge estimates for Pine Valley.

Component	Estimated Value	Description/Method
Total Precipitation (P)	12 inches (472 KAFY)	PRISM-based mean annual precipitation estimate over the 1971-2000 time period (Heilweil & Brooks:Table A2-1).
Total Groundwater Recharge (R_i)	27 KAFY	Basin Characterization Model results totaled for the Pine Valley HA and averaged for 1940-2006 (Heilweil & Brooks:Table A4-1).

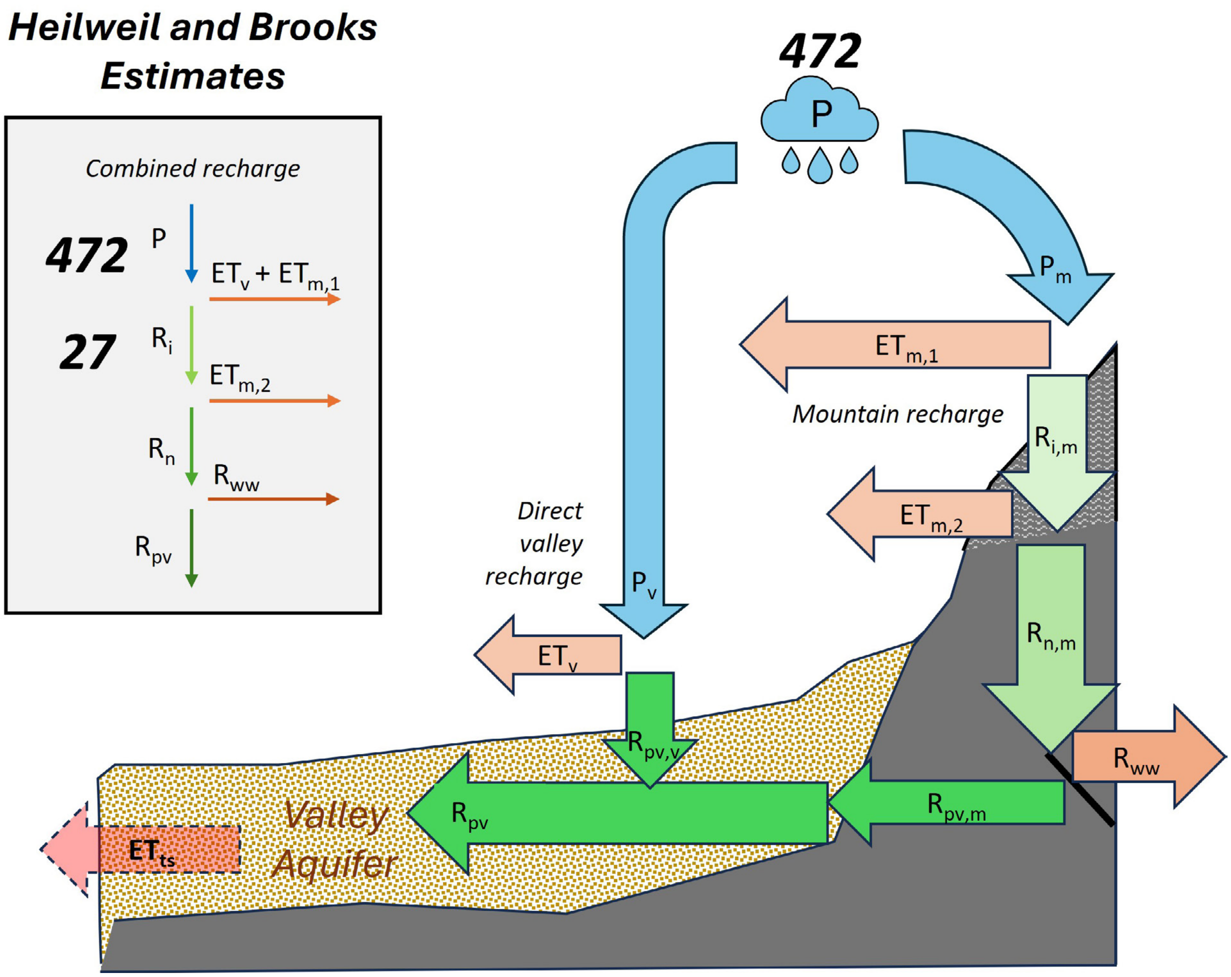


Figure 6. Values estimated by Heilweil and Brooks (2011) for Pine Valley water balance components, in thousands of acre feet per year (KAFY).

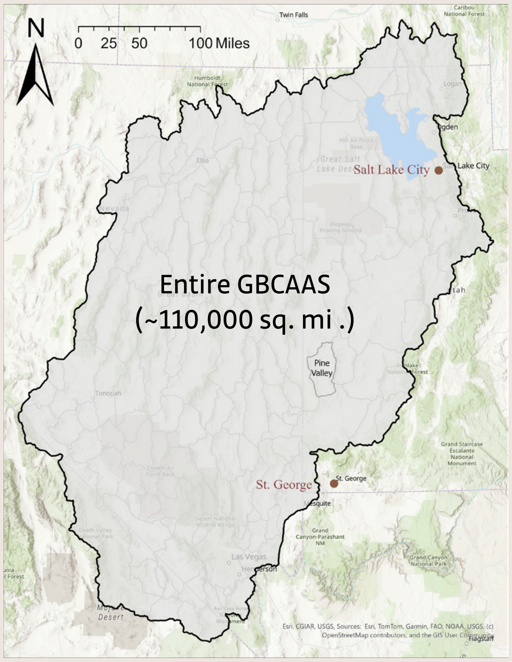
Brooks et al. 2014 *quick look*

Citations and Affiliations

L. E. Brooks, M. D. Masbruch, D. S. Sweetkind, and S. G. Buto, "Steady-state numerical groundwater flow model of the Great Basin carbonate and alluvial aquifer system," U.S. Geological Survey, 2014–5213, 2014. doi: 10.3133/sir20145213.

This study was completed by Lynette Brooks, Melissa Masbruch, Donald Sweetkind, and Susan Buto of the U.S. Geological Survey (USGS). It relies heavily on the data and estimates developed in the Heilweil and Brooks (2011) report [1] and is considered a companion report to that document (Figure 4).

Primary Study Area



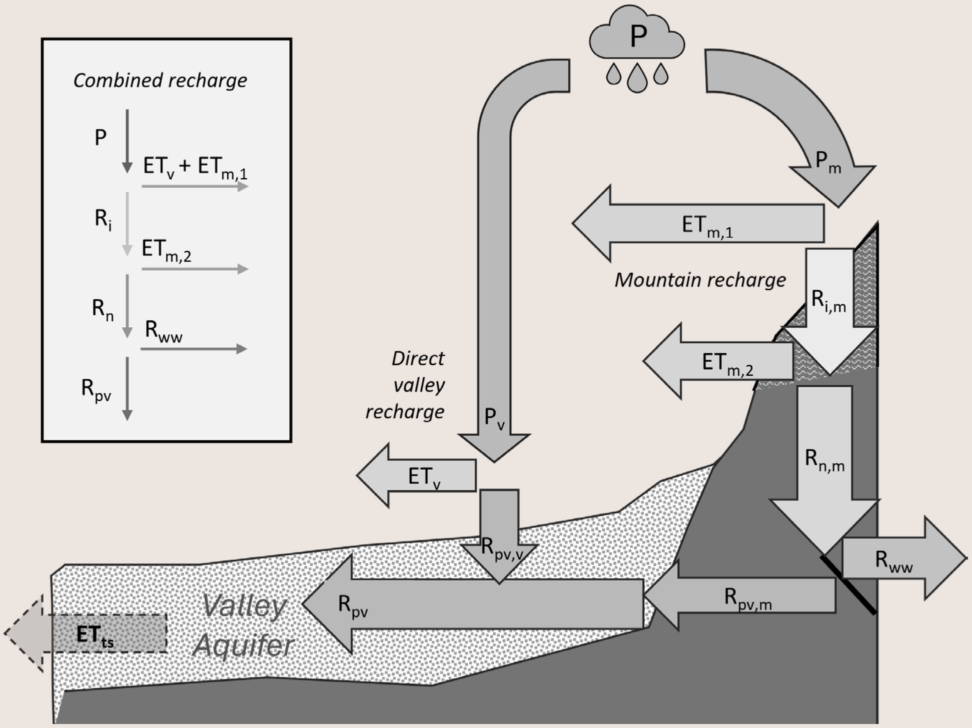
Study Type

Regional numerical groundwater flow model

Key Results

Component	Estimation Method	Estimate (in KAFY)	Description
Recharge	MODFLOW-2005 flow simulation calibrated to provide reasonable match to observed water levels and discharge rates	24 (R_i)	Total groundwater recharge/ total initial recharge

Key to Recharge Components



Brooks et al. 2014 *summary*

Scope/Geographic Context

This study develops a numerical groundwater flow model for the full ~110,000 sq. mi. Great Basin carbonate and alluvial aquifer system (GBCAAS) area. The report discusses the development, results, and assessment of the model. It describes how the model was constructed, presents the water level and discharge observations used for calibration, and explores the model's results and limitations.

Purpose

A primary objective of the Brooks et al. (2014) study was to evaluate whether a numerical groundwater flow model based on the Heilweil and Brooks (2011) water balances and conceptual understanding could reasonably simulate observed discharge and groundwater elevation data. The study is also intended to help assess regional groundwater availability.

Methods

Modeling and Water Balance Estimation

The study uses MODFLOW-2005 software with a 1-mi by 1-mi grid size and 8 vertical layers. The Brooks et al. (2014) model is known as the GBCAAS 1.0 model, as it is the first MODFLOW model developed for the full GBCAAS area. The software includes groundwater flow equations that are assembled into various software packages that can be selected for use in the model. GBCAAS 1.0 is a steady-state model that simulates groundwater flow, recharge, and discharge based on input parameters for each cell in the model grid.

Boundary Conditions and Model Inputs

Most of the study area boundary, the bottom layer of the model, and individual HA boundaries were set as no-flow boundaries.

Recharge estimates generated for each 270-m grid cell in the Heilweil and Brooks (2011) BCM were interpolated to a 1-mi grid size and used as specified-flow boundaries. MODFLOW-2005's Recharge Package was used to set these types of boundaries.

Groundwater discharge via ET_g or discharge to springs, streams, and lakes was modeled via head-dependent boundaries using the Drain Package. ET_g discharge rates were based on ET_g observations and estimates reported in Heilweil and Brooks (2011). Drain Package inputs were set such that ET_g was only able to occur when groundwater was between 5 to 40 feet below ground. Discharges from springs were only simulated for springs with flows of 300 gal/min or greater. Both valley and mountain springs that meet this flow criteria are included in the GBCAAS 1.0 model. GBCAAS 1.0 also simulates stream discharge in both mountain and valley areas. It uses the River Package to set head-dependent boundaries for streams. Very small streams and consistently intermittent streams were not modeled. No streams were explicitly modeled in the Pine Valley HA, and the closest modeled spring to Pine Valley is Wah Wah Springs.

Specified-head boundaries were used for large lakes (e.g., Utah Lake, Great Salt Lake); none of these are located near Pine Valley.

Hydraulic properties for the 8 vertical model layers were set using the Hydrogeologic-Unit Flow Package. The Horizontal-Flow Barrier Package was used to set groundwater flow barriers associated with features such as faults. For the Pine Valley HA, flow barriers were set along the fault that runs north-south along the western base of the Wah Wah Mountains, and along another north-south fault located near the northwestern corner of the HA (Brooks et al.2014: Fig 18).

Calibration

This study relies on various sets of observed data that represent steady-state conditions for model calibration. These include:

- Measured water levels in wells. Data at a total of 1,529 well locations throughout the GBCAAS were used. For the Pine Valley HA, water levels at 1 well with a 1960-1995 period of record were used (Brooks et al. '14: Fig. 19; Table A2-1).
- Measurements of average spring discharge at 158 total springs in the GBCAAS; none of these are in Pine Valley. At Wah Wah Springs (the closest modeled spring to Pine Valley), an average discharge value of 724 AFY (reported as 86,400 cubic feet per day; Brooks et al. 2014: Table A1-2) was used for calibration. Brooks et al. (2014:Table A1-9) cites a 1974 Wah Wah Valley study[1] [21]the source for this data.
- Measurements of stream discharge at 53 locations in the GBCAAS (none in or near Pine or Wah Wah Valleys).
- Evapotranspiration of groundwater (ET_g) values were from estimates developed in the Heilweil and Brooks (2011) study. No ETg was modeled in Pine Valley. Estimates for Tule Valley HA and Sevier Desert HA, where recharge from Pine Valley is assumed to discharge, are 37,000 and 59,000 AFY, respectively (38,000 and 60,600 AFY including springs and rivers; Brooks et al. 2014: Table A1-1).

The GBCAAS 1.0 model was calibrated by using statistical analyses (nonlinear regression residual analysis) to compare modeled results with the observed data sets. Model input parameters were then adjusted to obtain the best overall fit between the model outputs and observations.

Key Results

Water Balance and Recharge Estimates

The calibrated GBCAAS 1.0 model was able to reasonably match the conceptual Heilweil and Brooks (2011) recharge estimates for the entire GBCAAS model domain. Specifically, overall simulated discharge for the entire GBCAAS matches the conceptual amount and simulated overall recharge matches within 10 percent. Most modeled discharge values match observations within 30%, and most modeled groundwater elevations are within one standard deviation (119 feet) of observations. We provide the GBCAAS 1.0-simulated recharge estimate for the Pine Valley HA in our Table 6 and our Figure 7 below. This simulated estimate of 24 KAFY is slightly lower than the Heilweil and Brooks (2011) conceptual estimate of 27 KAFY. No other individual Pine Valley water budget component estimates are provided in the Brooks et al. (2014) report.

Assumptions and Limitations

The Brooks et al. (2014) study emphasizes that it was focused on regional-scale groundwater flow rather than detailed assessments at the individual HA level. It suggests that additional HA-scale information should be considered when making local-scale groundwater management decisions. The study also points out that calibration data is very limited and that important local-scale features may be misrepresented when aggregated into the 1-mile sized model grid cells.

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[1] Specifically, Brooks et al. (2014) cites the Stephens (1974) value for "Wah Wah Ranch No. 1" as the data source. Stephens (1974:Table 8) reports a value of 450 GPM for that site. 450 GPM = 726 AFY.

Table 6. Brooks et al. (2014) recharge estimate for Pine Valley.

Component	Estimated Value	Description/Method
Total Groundwater Recharge (R_i)	24 KAFY. (Brooks et al. 2014:Table A3-2)	Simulated by GBCAAS-1.0, a numerical groundwater flow model, using MODFLOW-2005 software

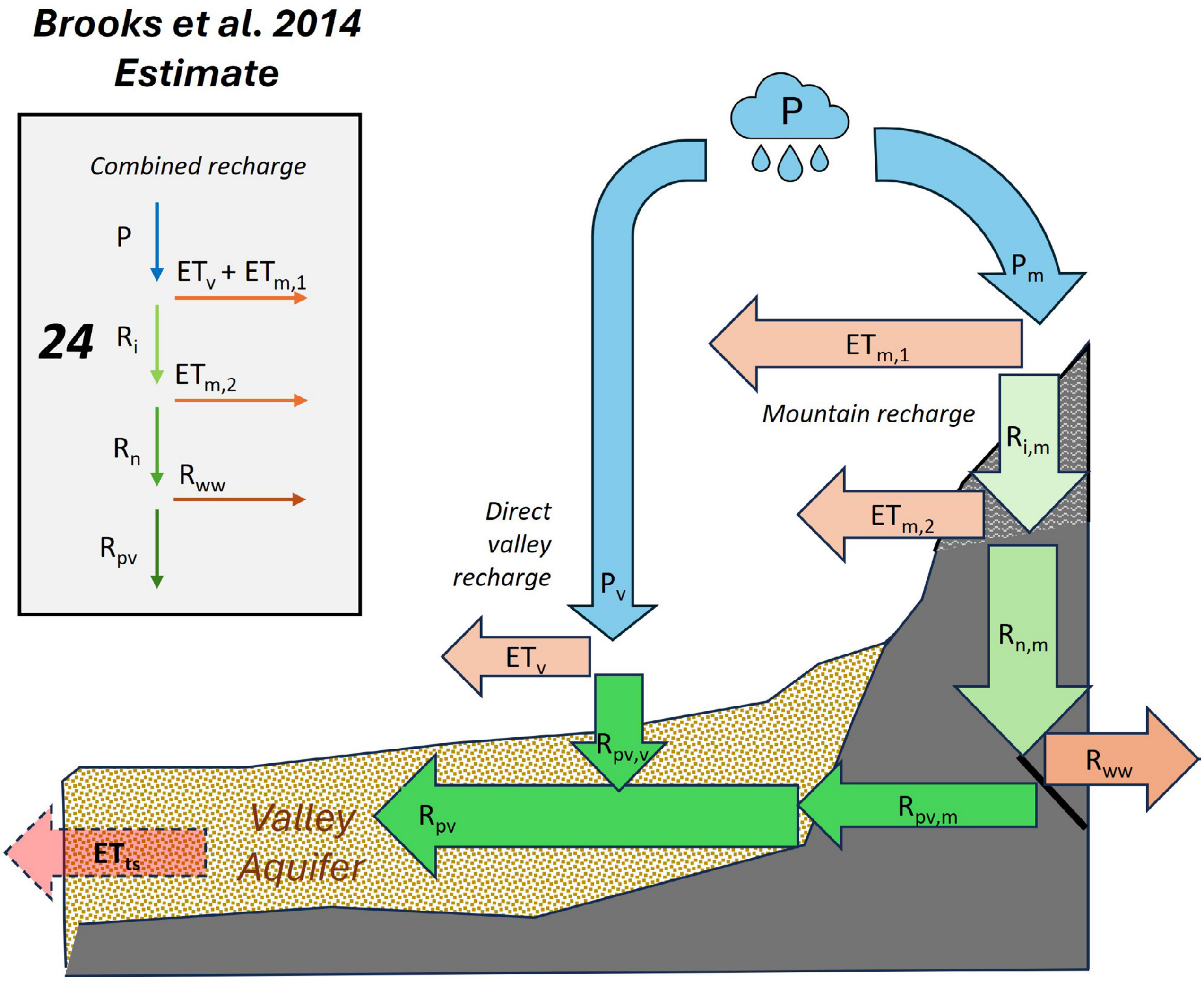


Figure 7. Value estimated by Brooks et al. 2014 for Pine Valley total groundwater recharge (Ri), in thousands of acre-feet (KAFY)

Brooks 2017/ Gardner et al. 2020

Citations and Affiliations

P. M. Gardner, Marston, Thomas M., S. G. Buto, and L. E. Brooks, "Hydrogeologic and Geochemical Characterization of Groundwater Resources in Pine and Wah Wah Valleys, Iron, Beaver, and Millard Counties, Utah," U.S. Geological Survey Scientific Investigations Report 2019–5139, 2020. [Online]. Available: https://pubs.usgs.gov/sir/2019/5139/sir20195139.pdf

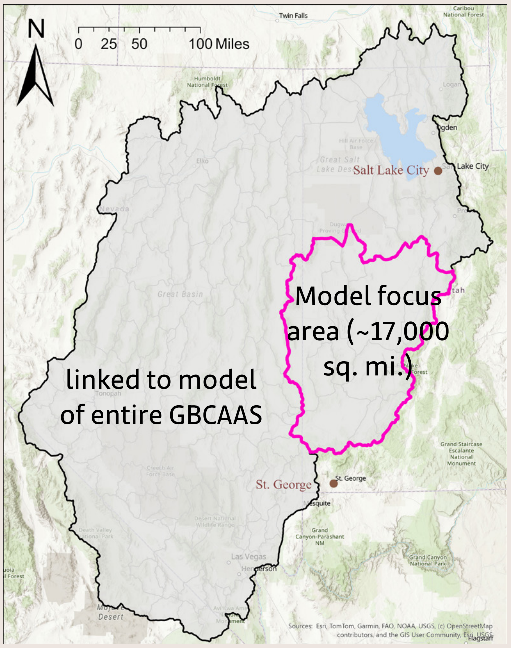
This study was completed by Philip Gardner, Thomas Marston, Susan Buto, and Lynette Brooks of the U.S. Geological Survey (USGS). It was prepared in cooperation with Utah Department of Natural Resources, Bureau of Land Management (BLM), and Central Iron County Water Conservancy District.

L. E. Brooks, "Groundwater model of the Great Basin carbonate and alluvial aquifer system version 3.0: Incorporating revisions in southwestern Utah and east central Nevada," U.S. Geological Survey, 2017–5072, 2017. doi: 10.3133/sir20175072.

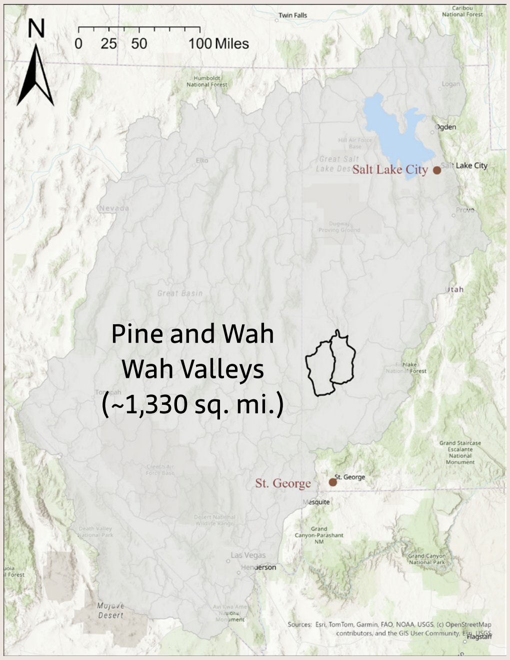
This study was completed by Lynette Brooks of the USGS. It was prepared in cooperation with the Utah Department of Natural Resources and the BLM.

For the purposes of our groundwater studies summary document, the Brooks (2017) and Gardner et al. (2020) studies are described in a single section and are collectively referred to as the Brooks/Gardner studies. This is because the Gardner et al. (2020) study was primarily undertaken in support of the Brooks (2017) groundwater modeling effort[2] and because the Brooks/Gardner studies provide a single set of water balance estimates for Pine Valley. We consider these publications companion reports (Figure 4).

Brooks 2017 Primary Study Area



Gardner et al. 2020 Primary Study Area



Brooks 2017 Study Type

Local updates to regional numerical groundwater flow model

Gardner et al. 2020 Study Type

Investigative data collection and analysis. Results used as input into Brooks (2017) model.

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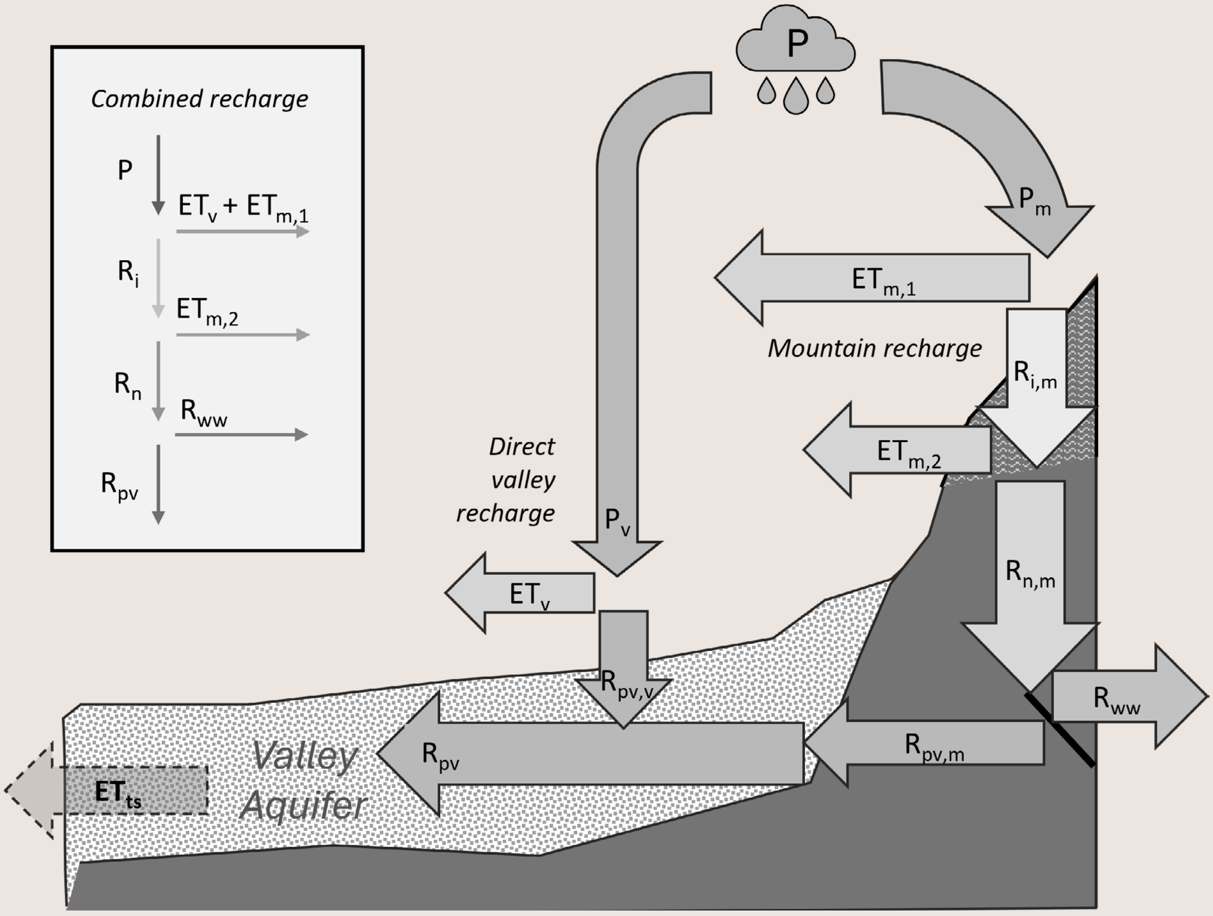
2 The data described in Gardner et al. 2020 report was available prior to the Brooks (2017) study, but its publication was delayed due to USGS staff changing jobs. The Brooks (2017) report cites much of the information presented in Gardner et al. 2020 as "Philip Gardner, U.S. Geological Survey, written commun., September 25, 2014" and "Philip Gardner, U.S. Geological Survey, written commun., July 21, 2016."

quick look

Key Results

Component	Estimation Method	Estimate (in KAFY)	Description
Precipitation	Gridded PRISM data for 1981-2010 (Gardner:5)	510 (P)	Total precipitation (=Pm + Pv)
Recharge	MODFLOW-LGR simulation using updated Pine Valley, Wah Wah Valley, Tule Valley, and Sevier Lake calibration data (Brooks 2017: Table 2)	11 (Rpv)	Recharge to valley aquifer of Pine Valley

Key to Recharge Components



Brooks 2017/ Gardner et al. 2020 *summary*

Scope/Geographic Context

The Gardner et al. (2020) study focuses on the Pine and Wah Wah Valley Hydrologic Areas (HAs), an area of about 1,330 square miles (see Figure 1). The report provides updated information on the hydrogeology of these HAs. Specifically, it makes several contributions: it presents an updated groundwater level map based on new groundwater depth measurements; analyzes temporal trends in groundwater levels; collects and analyzes discharge information at several springs; provides updated ETg (evapotranspiration of groundwater) estimates for the Tule Valley and Sevier Lake areas where groundwater from Pine and Wah Wah Valleys is assumed to discharge; analyzes the groundwater geochemistry of various wells and springs in the study area; and, compares simulated water balance estimates to Stephens' (1976) conceptual estimates.

The Brooks (2017) study describes the GBCAAS 3.0 modeling effort. GBCAAS 3.0 uses revised information for Parowan, Pine and Wah Wah Valleys to update and refine earlier versions of the GBCAAS model (see section on Brooks et al. (2014), above). The GBCAAS 3.0 is a large-scale numerical groundwater flow model of the approximately 110,000 square mile GBCAAS. However, the focus area for model refinement was limited to 13 HAs comprising the southern part of the Great Salt Lake Desert regional flow system – a much smaller area about 1/5 the size of the entire GBCAAS (see Figure 1).

Purpose

The focus of the Gardner et al. (2020) study is to provide a better understanding of the hydrogeology of Pine and Wah Wah Valleys in light of the proposed West Desert Pipeline and Pine Valley Water Supply projects that would develop and pipe groundwater to Iron County. The study is intended to support decision-making about those projects by providing improved conceptual hydrogeologic information and informing the updated GBCAAS 3.0 numerical groundwater flow model developed by Brooks (2017).

The purpose of the Brooks (2017) report is to document the GBCAAS 3.0 model revisions and results. For Pine and Wah Wah Valleys, it is intended to provide revised recharge estimates and to model the effects of the proposed pipeline projects on the GBCAAS groundwater flow system.

Methods

Methods discussed in the Precipitation, Spring/Stream Discharge, Groundwater Levels, Geochemistry, and Evapotranspiration subsections below are all described in the Gardner et al. (2020) report. Methods discussed in the Modeling and Water Balance Estimation subsection are from Brooks (2017).

Precipitation

The Gardner et al. (2020) study used PRISM gridded precipitation data for the 1981-2010 time period to estimate average annual precipitation for Pine Valley and for Wah Wah Valley. The study presents a map of the PRISM data precipitation ranges (Gardner et al.:Fig 2).

Spring/Stream Discharge

Spring discharge was measured at 11 springs for purposes of developing a groundwater level map of the study area. Spring discharge trends were evaluated for the 2013-2016 period at two study area springs: Pot Sum Pah in

Methods *cont.*

Pine Valley and Wah Wah Springs in Wah Wah Valley (Gardner et al.: Fig 7). No stream discharge measurements were collected or analyzed.

Groundwater Levels

Water level measurements were collected at a total of 63 wells to develop the study area water level map. Measurement dates, water levels, and location information are provided (Gardner et al.; Apdx A; Figure 4). Water level trend information for a subset of wells (3 in Pine Valley, 4 in Wah Wah Valley) was analyzed for the period 1976-2016 based on the newer measurements and historic water level information available via the National Water Information System (NWIS). Results are presented in Fig 6 of Gardner et al. (2020).

Aquifer Transmissivity

Pump tests were conducted at 10 valley aquifer wells in Pine and Wah Wah Valleys, seven of which are located in southern Pine Valley in the general area where the PVWSP is proposed. The pump tests were used to calculate specific capacity and then converted to transmissivity estimates using storage coefficients. Pump tests and the Cooper and Jacob (1946) method [22] were used to calculate transmissivity for two Pine Valley wells drilled into bedrock.

Geochemistry

Geochemistry information for 12 wells and 12 springs was obtained via both field and laboratory analysis methods. Thirteen of these sites are located in Pine Valley, the remainder in Wah Wah Valley. Nine of the 13 Pine Valley sample sites represent mountain groundwater and four come from deeper valley groundwater sites.

A multi-parameter data collection sensor was used to collect field data including water temperature, specific conductance, and pH. Water samples were collected and sent for lab analysis of major ions, nutrients, trace metals, tritium, helium, carbon-14, oxygen-18, deuterium, and noble gases. Analyses were completed by the National Water Quality Laboratory, the University of Utah's Dissolved Gas Laboratory, and the Woods Hole Oceanographic Institution McLean Laboratory. The report includes details about site locations and sample dates (Gardner et al.: Table 5; Fig 10).

Evapotranspiration from Groundwater

No groundwater discharges within Pine Valley; rather, it is presumed that the groundwater that leaves Pine Valley eventually discharges as evapotranspiration (ET_g) in groundwater discharge areas (GDAs) in Tule Valley and the area around Sevier Lake. Therefore, an accurate estimate of ETg to these GDAs is important for determining the water budget for Pine Valley. The Gardner et al. (2020) study re-assessed ETg in these GDAs. Specifically, the GDAs were mapped at a scale of about 1:24,000 using 2011 aerial imagery as a base map. To the extent possible, the areas were visited in the field and GPS points were collected along the boundary of phreatophytic (water-loving) vegetation that defines each GDA. Additional points, as well as photos and notes, were collected to map specific vegetation types present within each GDA. Field data were supplemented with aerial and satellite imagery to prepare complete GDA map information.

Specific ET rate ranges were initially assigned to each vegetation/land cover type within the GDAs. These ranges were based on values reported in the literature (Gardner et al.: Table 2). The ET rates were refined based on Landsat imagery vegetation index information and one year of evapotranspiration measurements at six eddy covariance sites in eastern Nevada. Based on high total dissolved solids (TDS) results suggestive of evaporative enrichment, an ET_g rate of 0 was used for the Sevier Lake playa. After various analyses, the average Modified Soil Adjusted Vegetation Index (MSAVI) index (averaged for 2 summer Landsat images) was selected as having the best ability to predict ET and it was used to estimate spatially-distributed ET for the GDAs.

As a final step, average annual precipitation derived from data collected at a Tule Valley weather station for 2006-2009 was subtracted from the total ET estimate for each GDA to calculate ET_g. The updated ET_g values were used as inputs in the GBCAAS 3.0 model detailed below.

Modeling and Water Balance Estimation

The study uses MODFLOW-LGR software to refine a portion of the GBCAAS 1.0 model grid. The version of the model developed in the Brooks (2017) study is known as the GBCAAS 3.0. It retains the 1-mi by 1-mi grid size and 8 vertical layers and is a steady-state model that simulates groundwater flow, recharge, and discharge based on input parameters for each cell in the model grid. In addition to making changes to the inputs for Pine and Wah Wah Valley, the Brooks (2017) study also refined the Parowan Valley portion of the model to evaluate groundwater decline scenarios in Parowan Valley. This Groundwater Studies document primarily focuses on the portion of the Brooks (2017) study that involved Pine and Wah Wah Valley HAs.

Boundary Conditions and Model Inputs

The specified-flow and no-flow boundaries for GBCAAS 3.0 were largely kept the same as in GBCAAS 1.0 (Brooks et al. 2014). For GBCAAS 3.0, new ET_g information was used to adjust some of the head-dependent flow boundaries in the model refinement area. Specifically, the GBCAAS 3.0 uses revised ETg values for the Tule and Sevier Lake GDAs based on the ET_g analysis presented in Gardner et al. (2020). Adjustments to ETg were also made in Parowan Valley and Snake Valley HAs to reflect more recent data. The GBCAAS 3.0 model adjusted the software used for modeling evapotranspiration to use MODFLOW's Evapotranspiration Package instead of the Drain Package used in prior GBCAAS model versions. Some new data were used to set head-dependent flow boundaries for a few modeled springs and rivers, but none of these changes were in Pine Valley.

Calibration

The new water level information measured in Pine Valley area wells (Gardner et al. 2020, described above) was used in calibrating GBCAAS 3.0, along with other water level observations originally used to calibrate the 1.0 version of the GBCAAS model. For wells with multiple measurements, levels were averaged over the period of observation. Water level observations in approximately 10 wells in Pine Valley (Brooks 2017: Fig 13; Table 1-5) were used for calibration. This is a significant increase in calibration data relative to the single Pine Valley well used in GBCAAS 1.0 calibration.

Based on initial calibration runs of earlier model versions, it became apparent that too much flow was being simulated along the western side of Sevier Lake. It also appeared that too much Pine Valley recharge was being simulated and/or Pine Valley transmissivity values were too low.

To improve these inaccurate simulation results, the GBCAAS 3.0 model was calibrated by systematically comparing modeled results with observed and estimated data sets. A somewhat simplified version of the statistical analyses (nonlinear regression residual analysis) used to calibrate GBCAAS 1.0 was used for GBCAAS 3.0. Model input parameters such as transmissivity were adjusted to obtain the best overall fit between the model outputs and empirical observations.

Prediction

In addition to developing the steady-state version of GBCAAS 3.0, Brooks (2017) also ran a transient model to simulate groundwater response to pumping in Pine and Wah Wah Valleys for 14 multi-year stress periods (Brooks 2017:Table 1) for a total projection time of 5,000 years. The model generated annual predictions and results are presented for 62-year, 1,000-year, and 5,000-year scenarios. These simulations used constant pumping rates of 15,000 AFY from Pine Valley and 6,500 AFY from Wah Wah Valley, which match the approved water right applications for the Pine Valley Water Supply Project (PVWSP) and Wah Wah Valley phases of the proposed West Desert Pipeline.

Key Results

Model Evaluation

Based on assessing model residuals, the recalibrated GBCAAS 3.0 model successfully improved the fit between modeled and observed water levels in Pine Valley, Wah Wah Valley, Tule Valley, and Sevier Desert HAs. Fit to observed discharge including ET_g, springs, and rivers was good overall. However, simulated ETg for the Sevier Lake GDA was less than half of the estimate generated by the Gardner et al. (2020) study (Brooks 2017:Table 1-6). The report explains that this may be due to the fact that the Gardner et al. (2020) Sevier Desert ET_g estimates had about 35% error, and that they may have over-estimated the groundwater component of ET since there is likely also a surface water component (Brooks 2017:38).

Water Balance and Recharge Estimates

We summarize estimates of various water balance components from the Brooks/Gardner studies below in our Table 7 and in our Figure 8. The recalibrated GBCAAS 3.0 model simulated Pine Valley recharge as 11 KAFY, a significant reduction compared to the GBCAAS 1.0 estimate of 24 KAFY (Brooks et al. 2014). This reduction was made primarily to enable the model to better match measured water levels on the west side of Sevier Lake.

Table 7. Brooks (2017)/Gardner et al. (2020) water balance and recharge estimates for Pine Valley.

Component	Estimated Value	Description/Method
Total Precipitation (P)	510 KAFY	Based on 1981-2010 PRISM data. (Gardner et al.:5).
Recharge to valley aquifer of Pine Valley (R_{pv})	11 KAFY	MODFLOW-LGR simulation using updated Pine Valley, Wah Wah Valley, Tule Valley, and Sevier Lake calibration data. (Brooks 2017:Table 8).
Subsurface discharge to Wah Wah Valley (R_{ww})	Not addressed.	Simulated recharge values are for the overall individual HA boundaries
Change in groundwater storage	0	GBCAAS 3.0 model simulates groundwater budgets as steady-state
Average annual Tule and Sevier Lake[2] groundwater evapotranspiration (ETg)	Gardner et al. estimates: • 35 KAFY (Tule Valley GDA) • 10.5 KAFY (Sevier Lake GDA) GBCAAS 3.0 simulation: • 33.9 KAFY (Tule Valley GDA) • 4.3 KAFY (Sevier Lake GDA)	• Gardner: Mapping of GDAs, evaluation of vegetation indices and measured evapotranspiration, estimation based on one mean vegetation index value derived from two summertime Landsat images, and subtraction of precipitation based on 4 years of data at one Tule Valley weather station. ETg estimates are reported (Gardner:15). • GBCAAS 3.0: Recalibration of MODFLOW-LGR model (Brooks 2017:Table 2)

2 ETg is not a direct component of the Pine Valley water balance; however, we report these values because of their importance in calibrating the simulated recharge estimates for Pine Valley.

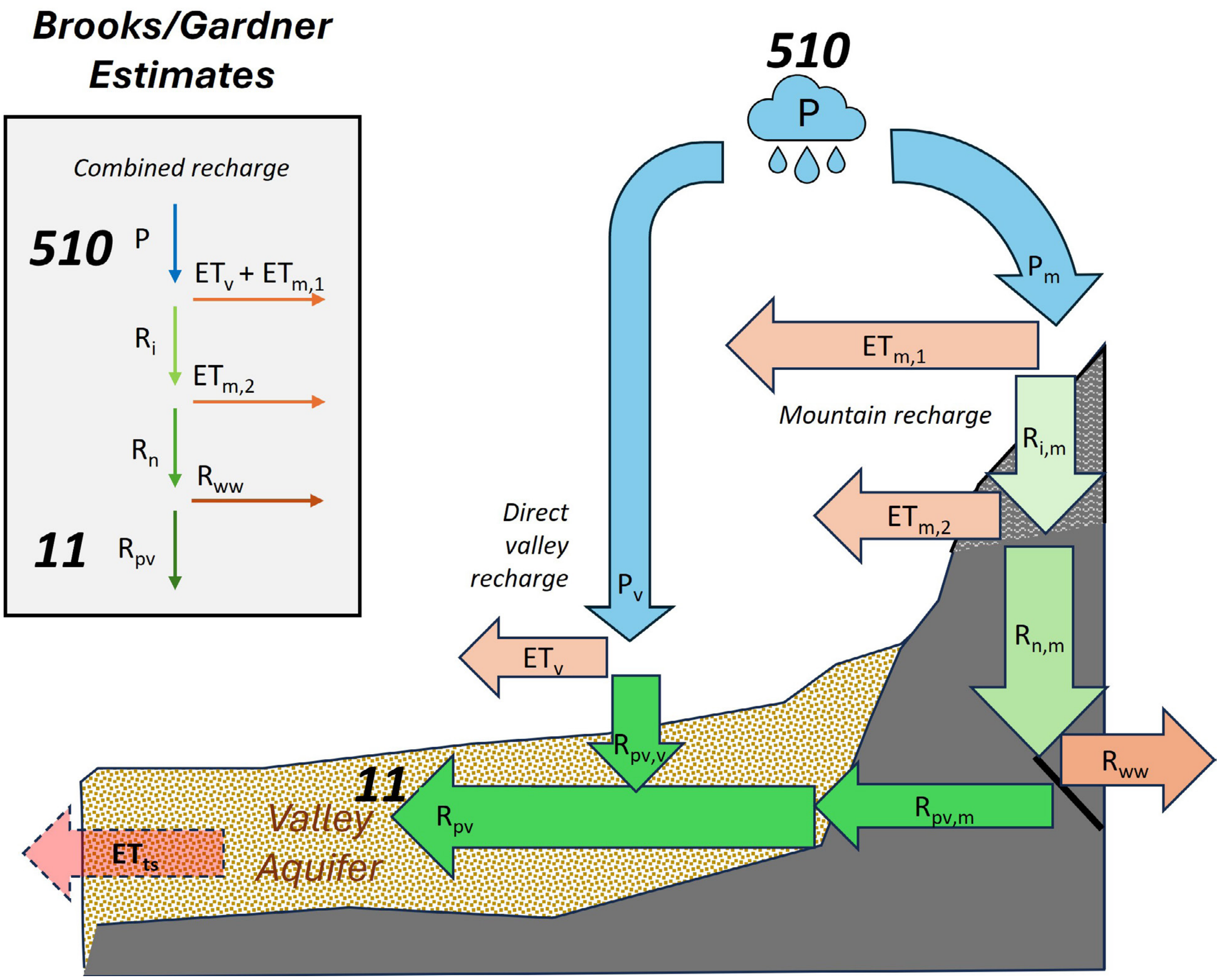


Figure 8. Values estimated by Brooks (2017) and Gardner et al. (2020) for Pine Valley water balance components, in thousands of acre feet per year (KAFY).

Key Results *cont.*

PVWSP Pumping Effects

The Brooks 2017 study modeled the effects of the proposed PVWSP pumping and piping of 15 KAFY and 6.5 KAFY from Pine and Wah Wah Valleys, respectively. At the end of the 5,000-year modeling period, the simulation shows a drop in groundwater levels of more than 5 feet over a 10,500 square mile area, with declines of more than 1,900 feet near the project wells. The impacts are more modest at the end of the initial 62-year scenario, with water level drops of 100-500 feet near the project wells and drops of 1 to 5 feet throughout most of the Pine and Wah Wah Valley HAs. The simulation predicts that Wah Wah Springs discharge would be reduced by 197 AFY (26% of the simulated 748 AFY steady state value) after 62 years, and that it would dry up completely in the 1,000-year model scenario (Brooks 2017:Table 12).

In 2021, Roux Associates, Inc. (Roux 2021) [23] used the Brooks 2017 GBCAAS 3.0 model to run a slightly different pumping scenario that simulates pumping in Pine Valley only (i.e., without Wah Wah Valley pumping). This model run was part of a 24-page technical memorandum regarding groundwater impacts of the PVWSP that was completed for Great Basin Water Network. Roux (2021) presents the results of their model run in a series of figures (Roux 2021:Fig 7,8,9) that highlight predicted changes to the Snake Valley water budget, groundwater flow direction, and subsurface underflow. They predict: 1) that the proposed PVWSP pumping will significantly increase underflow from Snake Valley to Pine Valley and will redirect Snake Valley's groundwater flow paths and 2) that underflow from Spring Valley (west of Snake Valley) into Snake Valley will be nearly twice as great as without PVWSP pumping. Roux (2021) also notes that the 15 KAFY proposed for PVWSP pumping is greater than the Brooks (2017) recharge estimate of 11 KAFY.

Mountain-Valley Aquifer Disconnect

Geochemistry and other results presented in Gardner et al. (2020) provide evidence that Pine Valley's mountain springs are perched, meaning they are largely disconnected from the valley aquifer. Several distinct types of evidence are discussed:

1. Mountain spring altitude and hydraulic gradient. The groundwater level map developed as part of the study (Gardner:Fig 4) shows very steep gradients along the interface where valley sediments meet the mountain bedrock. Connected groundwater systems do not typically have such steep gradients. The Gardner et al. (2020) study also cites the past observation (Stephens:15) that all of the 80 mountain springs mapped at that time are located above an elevation of 6,200 feet. This altitude is above the mountain interface with valley sediments and suggests the springs are perched and separated from the deeper groundwater in the valley aquifer.
2. Dissolved solids sampling. Results from dissolved solids testing show a distinction in the chemistry of valley versus mountain groundwater samples. Specifically, dissolved solids concentrations are higher in the mountain samples than in the valley samples. This result is the opposite of what would be expected in a well-connected system where mountain groundwater would typically pick up additional dissolved constituents along its long, slow flow path to the valley.
3. Noble gas temperatures. Most of the valley groundwater samples had higher noble gas temperatures (NGTs) than the mountain groundwater samples. NGT is indicative of the temperature of groundwater where it initially recharges and is typically stable throughout its flow path. The fact that the lower mountain groundwater NGTs are not preserved in the valley groundwater NGT results suggests perching/disconnection of the mountain groundwater system.

While the bulk of the scientific evidence suggests perching of mountain groundwater, the Gardner et al. (2020) study did find some evidence suggesting that local pathways of connection to the valley aquifer do exist. Specifically, one of the four valley groundwater sample sites had a relatively low NGT temperature. This is to be expected given the variability in permeability of the volcanic rocks that comprise the mountains surrounding the southern portion of the Pine Valley HA.

Assumptions and Limitations

Several assumptions and limitations are noted in the Gardner/Brooks studies:

- The Tule Valley and Sevier Lake GDA ETg estimates calculated by Gardner et al. (2020) and simulated by the GBCAAS 3.0 model (Brooks 2017) assume that Sevier Lake playa is disconnected (playa ETg=0) from regional groundwater. This assumption is based on samples collected by a mineral exploration company and its consultant in 2012 and 2013. These samples had much higher dissolved solids values than samples from nearby groundwater wells. If fresh groundwater from the regional aquifer system was discharging into the playa, dissolved solids results would be expected to be much more similar.
- The Gardner et al. (2020) study states that its Tule Valley and Sevier Lake ETg estimates have an uncertainty of plus or minus 35 percent.
- The recharge estimates simulated by the GBCAAS 3.0 model are only relevant for the valley aquifer and do not model mountain recharge that discharges via mountain springs and streams.
- The GBCAAS 3.0 model is scaled to its focus area (see our Figure 1) and not meant to predict effects at the individual grid-cell level. In addition, the 1-mile grid size means important local-scale features may not be represented by the model.
- Hydrogeologic data and calibration data availability is limited, particularly in some portions of the study area.

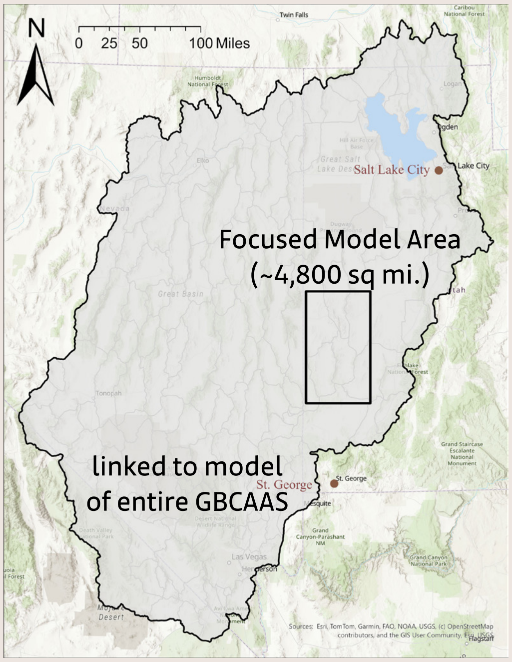
Formation 2021 *quick look*

Citations and Affiliations

[Formation] Formation Environmental, "Groundwater Resources Impact Assessment. Pine Valley Water Supply Project, Iron and Beaver Counties, Utah," Prepared for Transcon Environmental and Central Iron County Water Conservancy District on behalf of Bureau of Land Management, 2021.

The Formation (2021) study was prepared as part of the Bureau of Land Management (BLM) NEPA evaluation of the Pine Valley Water Supply Project (PVWSP) proposed by Central Iron County Water Conservancy District (CICWCD). The work was completed by a private environmental consulting firm with collaborative input from a Groundwater Technical Team including scientists and engineers with BLM, USGS, CICWCD, and other private firms.

Primary Study Area



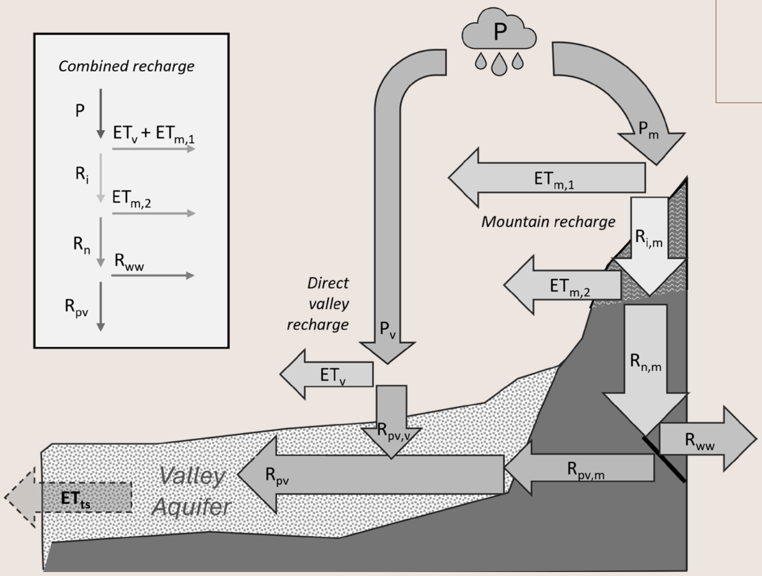
Study Type

Impact assessment/ investigative data compilation and analysis/ local numerical groundwater flow model

Key Results

Component	Estimation Method	Estimate (in KAFY)	Description
Precipitation	Average of 6 weather stations in/near Pine Valley with variable periods of record	388 (P)	Total precipitation (=Pm + Pv)
Recharge	Subtraction of average evapo-transpiration estimate from average precipitation estimate	17.7 (Rn)	Net groundwater recharge
		14.7 (Rpv	Recharge to valley aquifer of Pine Valley (=Rn-Rww)

Key to Recharge Components



Formation 2021 *summary*

Scope/Geographic Context

The report assesses impacts for several different geographic areas: a "Focused Model Area", a smaller "Area of Project Effect", and a larger "Study Area" (see our Figure 1 and our Figure 9). The Focused Model Area includes all of the Pine Valley and Wah Wah Valley Hydrologic Areas (HAs) as well as portions of the Snake Valley, Tule Valley, Sevier Desert, Milford, and Beryl-Enterprise HAs. This is the area used for development of an updated "child" groundwater model (see methods subsection below for more modeling details). The Area of Project Effect includes Pine and Wah Wah Valleys and small parts of Snake Valley and Beryl-Enterprise. This is the area where groundwater impacts from the PVWSP are predicted by the Formation (2021) model. Two slightly different Areas of Project Effect (Figure 9) were predicted for each of the two PVWSP action alternatives[3]. The Study Area encompasses the entire extent of all seven of the HAs listed above, and is the overall area used for impact assessment more generally.

Purpose

This study was completed to provide updated hydrogeologic information about Pine Valley to help assess groundwater-related impacts of the proposed PVWSP. It is intended to enhance the current understanding of the Pine Valley aquifer, develop a groundwater flow model capable of predicting the effects of consumptive groundwater withdrawals, and recommend monitoring and mitigation measures.

Methods

Precipitation

This study evaluated precipitation values recorded at weather stations compared to values based on PRISM gridded data products. The authors assembled recorded precipitation values at 17 stations located in and around Pine and Wah Wah Valleys and compared results to values extracted from PRISM data for the station locations (Formation:Table 3-9). The analysis showed that the PRISM values were consistently higher than the gage data – a result that matches the McEvoy et al. (2014) study [24] that found gage data under-reports the snow component of precipitation. After further analysis, the Formation study authors opted to estimate Pine Valley precipitation based on averaging precipitation gage data for 6 weather stations located in or immediately adjacent to the Pine Valley HA boundary. The averaging was done as a simple average calculation without weighting by area. The resulting annual average value is considered by the study authors to be a conservative (low) estimate for water balance, modeling, and impact analysis purposes (Formation:53).

Evapotranspiration

This study used Landsat imagery from 2005-2014 to estimate total evapotranspiration (ET) for Pine and Wah Wah Valleys, Sevier Lake, and most of Tule Valley. A total of 250 images were evaluated over this 10-year period using the Surface Energy Balance System algorithm. Data from 10 weather stations in/near Spring, Tule, Snake, Beryl-Enterprise, Milford and Wah Wah Valleys and near Ely, NV were used to supplement the Landsat imagery to generate a gridded (30-m grid size) map of daily ET estimates. These estimates were aggregated for the Pine Valley area to generate an estimated average annual total ET value.

Spring/Stream Discharge

The Formation (2021) study maps the locations of 268 seeps and springs within the areas of potential effect of the PVWSP alternatives (Formation:Fig 3-6;Fig 3-7). Discharge data are only presented for a small portion of these springs. Specifically, the study summarizes previously reported discharge data for 16 springs, with ten of

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[3] Details about the PVWSP alternatives are available in the BLM's draft EIS [23]

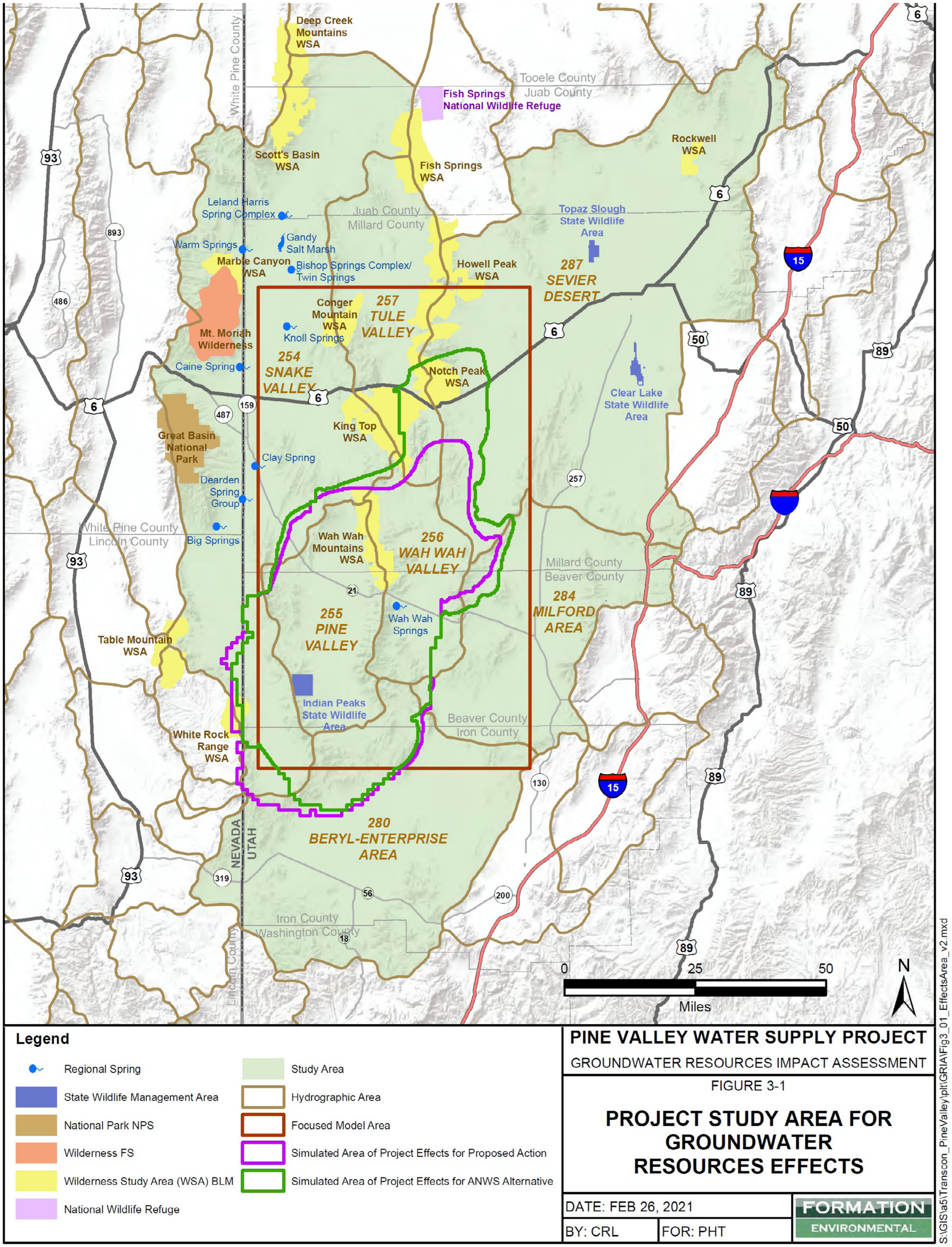


Figure 9. Map from the Formation 2021 study [6] showing the different areas evaluated for various aspects of the study

these listed as being in the Pine Valley HA (Formation:Table 3-3). The table cites a 2019 personal communication with R. Smith of the BLM as the source for the reported spring discharge information. Discharge measurement methods are not described. Figure 3-16 of the Formation (2021) report replicates Figure 7 of the Gardner et al. (2020) study, presenting temporal trends in spring discharge from 2013-2016 at Pot Sum Pah Spring in Pine Valley and Wah Wah Springs in Wah Wah Valley. The Formation (2021) report summarizes previously published stream discharge data (Formation:Section 3.7.1.1). No new discharge measurements were collected for this study.

Groundwater Levels

No new groundwater level data were collected for this report. Instead, the authors present (Formation: Figure 3-15) the same data shown in Figure 6 of the Gardner et al. (2020) study. The figure summarizes groundwater level trends from 1976-2016 for seven wells: 3 in Pine Valley, 4 in Wah Wah Valley. All of the Pine Valley wells are located in the deep valley aquifer.

Geochemistry

No new geochemical samples were collected or analyzed for this report. Instead, it summarizes and discusses the analyses described in the Gardner et al. (2020) study (Formation:44-46).

Aquifer Transmissivity

An accurate understanding of transmissivity (the rate at which groundwater moves through an aquifer) is important when developing groundwater models and predicting impacts of proposed pumping. It is a key aquifer characteristic that influences well productivity and the rate at which pumping will affect the surrounding water table. The study re-analyzes and summarizes transmissivity information (Formation:Table 3-5; Table 3-6) reported in Gardner et al. (2020). Formation (2021) used time series data of drawdown available for four of the tested wells (three in basin-fill, one in bedrock) and applied different estimation methods (confined Theis recovery and Cooper-Jacob Agarwal) to generate a different set of transmissivity results (Formation:Table A1).

Water Balance Estimation

The Formation (2021) study estimated net Pine Valley recharge (Rn) by subtracting the estimate of annual average evapotranspiration from the estimate of annual average precipitation and multiplying by a basin area of 472,200 acres. They estimated the subsurface outflow from the valley aquifer (ET_{ts}, also equal to R_{pv}) by subtracting the amount of recharge assumed to flow subsurface to Wah Wah Valley (R_{ww}) from their R_n estimate. Formation (2021) used the Stephens (1976) estimate of R_{ww} for this calculation.

Modeling

The Formation (2021) study used the Brooks 2017 GBCAAS 3.0 model as a “parent” model and developed a locally refined grid (child) model for Pine Valley. This MODFLOW-LGR model is known as the GBCAAS-PV and was used to evaluate the groundwater effects of PVWSP pumping compared to a baseline scenario.

The extent of the child model domain was chosen with input from the Groundwater Technical Team assembled for the study. Specifically, boundaries were established in locations that avoided spanning faults or breaks in aquifer properties. The overall child model grid wound up using a 0.04 sq. mi. (0.2 x 0.2 mi) grid cell size with an overall area of approximately 4,784 sq. mi. For comparison, the GBCAAS 3.0 parent model uses a 1 sq. mi. grid cell size over the entire ~110,000 sq.mi. GBCAAS area. GBCAAS-PV’s child model grid uses 16 vertical layers, compared to the 8 layers used in GBCAAS 3.0. GBCAAS-PV models groundwater flow for the entire GBCAAS area (Figure 1) using the refined “child model” information within the Focused Model Area.

Boundary Conditions and Model Inputs

Much of the GBCAAS-PV modeling approach was the same as used in the GBCAAS 3.0 parent model. As with the GBCAAS 1.0 and 3.0 models, the GBCAAS-PV model uses MODFLOW's Recharge Package to set recharge as a specified-flow boundary. The GBCAAS 3.0 recharge parameter values were increased to better match the higher overall recharge estimates of the Formation (2021) study versus the recharge value simulated by GBCAAS 3.0 (Brooks 2017). Specifically, for Pine Valley, GBCAAS-PV used Formation's 17.7 KAFY estimate (an estimate of net groundwater recharge, R_n), for setting boundary conditions (Formation:A-80).

ET_g is simulated by GBCAAS-PV the same way as GBCAAS 3.0: it uses MODFLOW's Evapotranspiration Package and the same ET_g estimates (from Gardner et al. 2020) to set boundary conditions. GBCAAS-PV simulates Wah Wah Springs and Clay Spring via head-dependent boundaries in vertical layers 1 and 2 using MODFLOW's Drain Package and sets each spring area as a single model cell. Geologic information was digitized and used to update the hydrogeologic unit information for the additional vertical layers and smaller grid size of the GBCAAS-PV's child model.

Calibration

The GBCAAS-PV model was calibrated using water level observations in wells, discharge in springs, and ET_g estimates that were assumed to represent steady-state conditions. The Formation (2021) study used the same water level observations as GBCAAS 3.0 after checking NWIS to confirm the accuracy of the well information. The GBCAAS-PV model increased the Wah Wah Springs discharge used for calibration, using a value of 1,800 AFY versus 84,600 cubic feet/day (724 AFY) used as the model observation in GBCAAS 3.0; otherwise, it used the same calibration discharges for springs as GBCAAS 3.0.

GBCAAS-PV calibration used the same statistical techniques used for GBCAAS 3.0. Adjustments were iteratively made to various model inputs including recharge, hydraulic conductivity, vertical anisotropy, and conductance, to achieve the best overall match with observed values. The model was calibrated using a 1,000 year "long-term equilibrium" stress period intended to represent steady-state pre-groundwater development conditions.

Prediction

Methods used to predict the effects of PVWSP pumping are described in section A5 of the Formation (2021) report. The model assumes an average annual pumping rate of 1,000 AFY at each of 15 production wells. This scenario is simulated for 50 years followed by a 450-year recovery period with no pumping. Four stress periods were modeled: two pre-project periods used for model calibration; one during PVWSP pumping operation; and one during recovery from PVWSP pumping. Modeling used one-year time steps (Formation:A-73). Startup pumping at the proposed six initial production wells was modeled using a monthly timestep for the stress periods.

Key Results

Water Balance and Recharge Estimates

The Formation (2021) water balance value estimates are summarized below in our Table 8 and Figure 10. The estimated average annual precipitation value is lower than estimates reported in previous studies and is considered by the Formation (2021) study authors to be a conservative (low) estimate. Despite the lower precipitation estimate, Formation's 14.7 KAFY estimate of recharge to the valley aquifer of Pine Valley (R_{pv}, calculated using a Landsat-based evapotranspiration estimate for the Pine Valley HA) is higher than the most recent USGS R_{pv} estimate of 11 KAFY (simulated with the Brooks 2017 GBCAAS 3.0 model).

Model Evaluation

The GBCAAS-PV model was calibrated using Formation's larger recharge estimates for Pine and Wah Wah Valleys (specifically their Pine Valley Rn estimate of 17.7 KAFY) rather than the R_{pv} value of 11 KAFY simulated in GBCAAS 3.0 (Brooks 2017). Because of this, the GBCAAS-PV- simulated flows from Pine and Wah Wah Valley HAs to other HAs are also higher (Formation:Table A8). The study also emphasizes that the final GBCAAS-PV calibrated hydraulic conductivity parameters for the model areas where pump tests were conducted are significantly higher than those in GBCAAS 3.0 and provide a better match with estimated transmissivity values (Formation:A-47).

Table 8. Formation (2021) water balance and recharge estimates for Pine Valley

Component	Estimated Value	Description/Method
Total Precipitation (P)	388 KAFY (9.86 inches)	Based on averaging 6 rain gage stations in/near Pine Valley over their periods of record
Net Groundwater Recharge (R_n)	17.7 KAFY (0.45 inches)	Subtracting evapotranspiration estimate from precipitation estimate to get net average annual recharge rate of 0.45 inches
Subsurface discharge to Wah Wah Valley (R_{ww})	Not addressed.	Simulated recharge values are for the overall individual HA boundaries
Total Evapotranspiration ($ET_v + ET_{m,1} + ET_{m,2}$)	370 KAFY (9.41 inches)	Landsat data/ Surface Energy Balance System algorithm; averaged for 2005-2014 time period
Discharge by wells	5 AFY ("negligible")	
Subsurface discharge to Wah Wah Valley (R_{ww})	3 KAFY	Cites Stephens (1976) and Brooks (2017)
Recharge to valley aquifer of Pine Valley (R_{pv})	14.7 KAFY	Subtract subsurface discharge to Wah Wah Valley from net recharge estimate
Evapotranspiration of Pine Valley groundwater in Tule and Sevier Valleys (ET_{ts})	14.7 KAFY	Reported as net groundwater outflow mostly northward (Formation:Table 3-19)

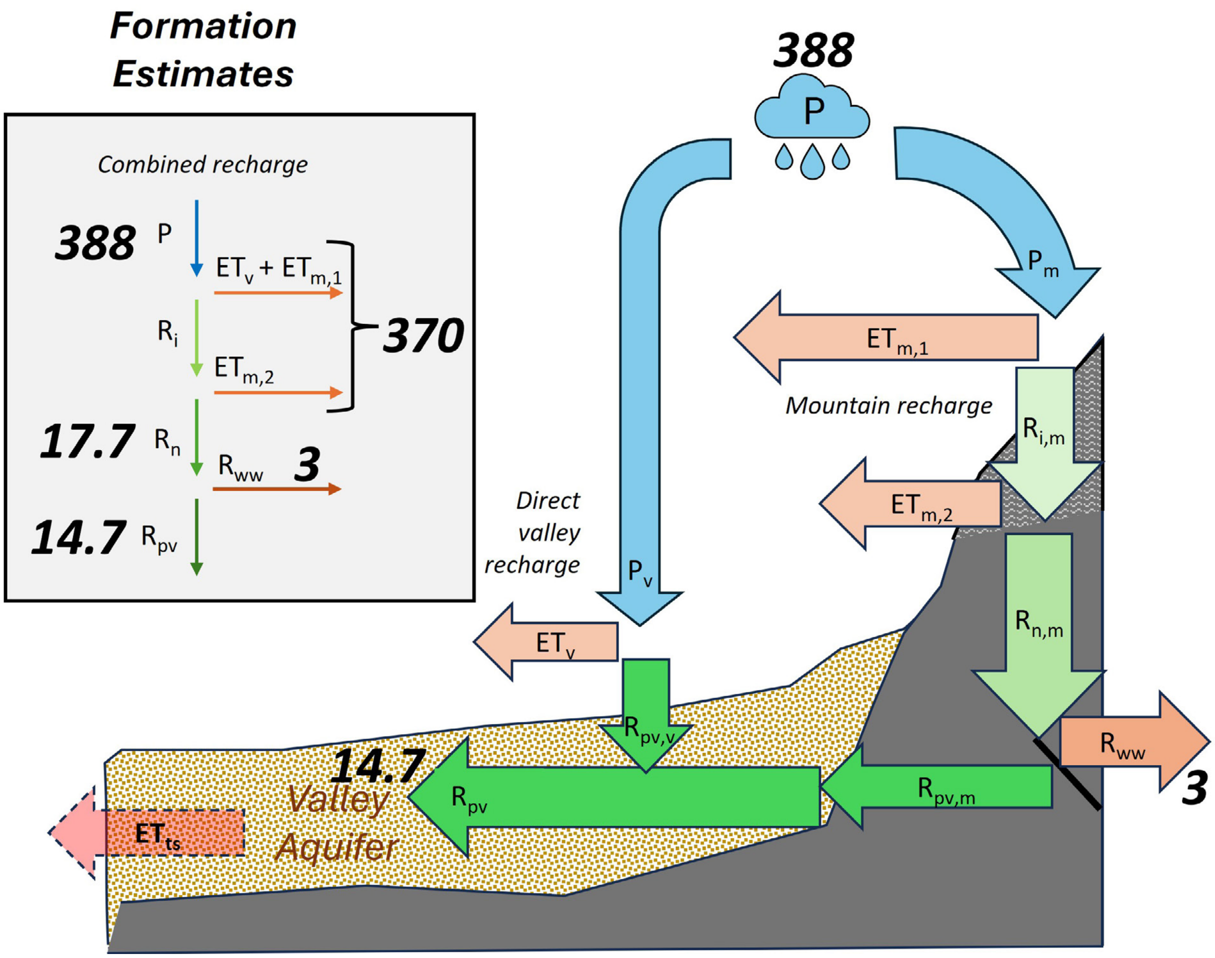


Figure 10. Values estimated by Formation (2021) for Pine Valley water balance components, in thousands of acre feet per year (KAFY).

Key Results *cont.*

Geochemistry

The Formation (2021) study describes the results of the Gardner et al. (2020) geochemical analyses. These analyses indicate that mountain groundwater samples are of modern and mixed ages, while valley groundwater samples are older (Holocene or Pleistocene age). The groundwater aging results also support the general understanding that valley groundwater flows from south to north, with sample ages increasing in this direction.

However, the Formation (2021) study cautions that many of the samples that the Gardner et al. (2020) geochemistry results are based on were collected in wells with long screen intervals (i.e., long perforated sections where groundwater can enter). These samples therefore represent groundwater from a mix of depths in the well. Because deep groundwater is typically older than shallow groundwater, the samples also likely reflect a mix of groundwater ages rather than providing a consistent assessment of the spatial distribution of groundwater age in the uppermost (youngest) portion of the aquifer.

Aquifer Transmissivity

Formation's re-analysis of pump test data using alternate methods generated transmissivity values higher than the original Gardner et al. (2020) calculations. The Formation (2021) report also reviewed historical transmissivity estimates made in prior studies (Formation:Table 3-6). Some of those historic values match Gardner et al. (2020) estimates while others more closely match Formation (2021) updated estimates. The Formation (2021) report authors suggests that their own updated estimates are more reliable than previous estimates (Formation:39).

PVWSP Pumping Effects

At the end of the initial 50-year pumping period, Formation's GBCAAS-PV model shows a maximum groundwater level drop of 350-400 feet near the production wells. An area of approximately 84 square miles would be affected by drawdowns of more than 100 feet. The discharge of Wah Wah Springs is expected to decrease by a maximum of 14-15% about 90 years after pumping starts. This would drop estimated spring discharge from 1,800 AFY to 1,525 -1,550 AFY

Assumptions

Water Balance

- 3,000 AFY of groundwater is assumed to discharge subsurface east into Wah Wah Valley. The Formation (2021) report cites Stephens (1976) when making this assumption. Stephens does not provide any explanation for how it was determined that 3,000 AFY of the total 5,000 AFY of recharge estimated for the Wah Wah subarea drains to Wah Wah Valley.

GBCAAS-PV Model

Springs:

- The model assumes Wah Wah Springs is a regional spring system connected to the valley aquifer with a discharge of 1,800 AFY. The 1,800 AFY value was determined by adding 200 AFY of ET (based on the Formation ET analysis) to the 1,600 AFY (2.2 cfs) discharge measurement reported by Gardner et al. (2020:13).
- Other than Wah Wah Springs and Clay Spring, the model assumes all other springs located in the model focus area are perched and disconnected from the regional valley aquifer.

Groundwater conditions:

- Recharge (Rn) is assumed to be a constant 17.7 KAFY
- Groundwater levels are assumed to be steady at the time PVWSP pumping begins

Study Recommendations

The Formation (2021) report does not include specific recommendations for additional scientific studies, but Section 1.4.2 of the report provides a summary list of data gaps and areas of uncertainty with respect to Pine Valley groundwater. Section 6 of the report provides a strategy for adaptive management, monitoring, and mitigation measures to implement as part of the PVWSP.

Study Comments and Concerns

In 2022, Roux Associates, Inc., (Roux 2022) [26] prepared a 9-page technical memorandum for Beaver County that documented technical comments and concerns regarding PVWSP impact analyses described in the Formation (2021) study and in the draft EIS [24]. Roux (2022) highlights the data gaps and uncertainties inherent in the Formation modeling scenario. These include a lack of detailed data with respect to aquifer properties, geologic faults not represented in the model, uncertain evapotranspiration and recharge estimates, and uncertainty associated with the model's assumption of constant transmissivity. Many of the data gaps highlighted in Roux (2022) are also identified in the Brooks 2017/Gardner et al. 2020 studies (see previous section of this document).

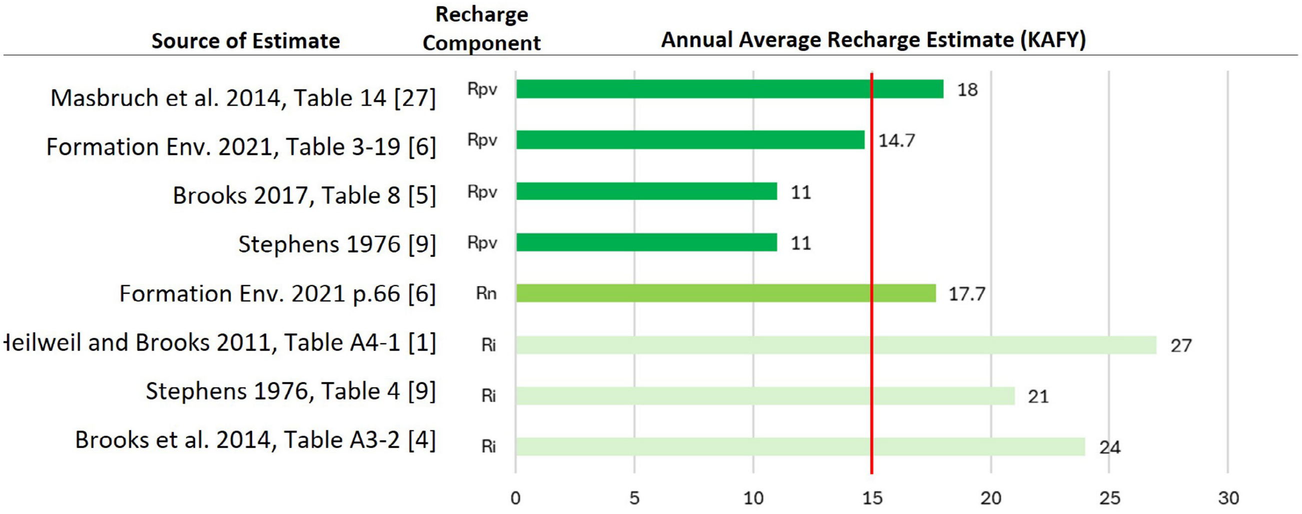
Key Results *cont.*

Roux (2022) also criticizes the Formation (2021) study's choice to limit the modeling timeframe to only 50 years of pumping and suggests a longer model run that approaches steady state would be a better approach for assessing PVWSP impacts. Roux (2022) also emphasizes the lack of field data for springs and suggests there is a need to expand the GBCAAS-PV model area to include more distant spring systems such as Fish Springs National Wildlife Refuge. It also questions the ability of Formation's proposed adaptive management approach to detect and mitigate groundwater impacts in a timely manner.

Integrated Summary

As described in detail above, various scientific studies completed between 1976 and 2021 present a wide range of groundwater recharge estimates for Pine Valley (Figure 11). R_{PV} is the component that recharges the groundwater in the valley aquifer. The most recent estimates of R_{PV} are 11 KAFY [5] and 14.7 KAFY [6]. Studies have also provided estimates of total groundwater recharge for the entire basin (Ri) of 27 [4], 24 [4], and 21 KAFY [9]. Estimated values vary depending on data sets and methods used as well as which component of total recharge they represent. Further, all of these estimates are subject to the uncertainties and assumptions presented in previous sections of this document. When considering the estimates, it is important to keep in mind that even simple differences, like using a different set of years to calculate annual precipitation, can change the resulting recharge estimate.

The studies summarized above each highlight various uncertainties or areas where data are lacking, and some also include recommendations for additional research and data collection to address those uncertainties. We provide a select list of research topics and their relevance to uncertainties, assumptions, and estimates to highlight areas that could benefit from additional work (Table 9). The monitoring plan included in the Formation 2021 study [6] and in the PVWSP Draft Environmental Impact Statement [24] also addresses some of these topics.



Key to Recharge Components:

- 🟩 *__Rpv__ is recharged groundwater understood to flow subsurface out of Pine Valley to the north; it recharges the water in the valley aquifer. Reported as "subsurface outflow from Pine Valley [9]; simulated groundwater recharge [27] [5]; "Pine Valley net groundwater outflow northward" [6];*
- 🟩 *__Rn__ equals Rpv plus the portion of groundwater understood to flow subsurface into Wah Wah Valley. Reported as "net groundwater recharge estimate" [6]*
- ☐ *__Ri__ equals Rn plus the groundwater understood to discharge/evapotranspire as perched mountain springs and streams; reported as total groundwater recharge [9] [1] and "simulated groundwater recharge" [4]*

— *Red line indicates amount of CICWCD's Pine Valley water right*

Figure 11. Chart showing various Pine Valley recharge estimates. These estimates are subject to the uncertainties and assumptions presented in previous sections of this document

Table 9. Select further research topics

Location	Research Topic	Purpose and Relevance
Sevier Lake/ Playa	Investigate ET_g and groundwater geochemistry to help distinguish regional versus local groundwater components of evapotranspiration	• Help reduce the 35% uncertainty of the Gardner et al. (2020) Sevier Lake ET_g estimate used in the Brooks (2017) model. • Update/expand on the samples from 2012/2013 that underpin the Brooks (2017) assumption of Sevier Lake playa $ET_g=0$. • Refine calibration of groundwater models and associated estimates of recharge to the Pine Valley aquifer (R_{pv})
Wah Wah Springs	Investigate how much spring discharge is from valley versus mountain aquifers	• Provide data to evaluate the accuracy of the unverified assumption that 3 KAFY of Pine Valley recharge discharges subsurface to Wah Wah Valley; that assumption affects the R_{pv} estimates by Stephens (1976) and Formation (2021). • Inform evaluation of potential PVWSP impacts to Wah Wah Springs
Southern portion of Pine Valley HA	Investigate volcanic geology/ groundwater connectivity with adjacent HA	• Inform evaluation of potential PVWSP impacts to Beryl-Enterprise HA
General	Further investigate connectivity between mountain and valley aquifers; collect and analyze samples from groundwater wells with short screen intervals that consistently represent the uppermost portion of aquifer	• Provide consistent data to assess groundwater age and geochemistry in mountain versus valley aquifers • Inform evaluation of potential PVWSP impacts to mountain springs
General	Better characterize aquifer hydraulic properties (transmissivity, etc.)	• Update parameter inputs into groundwater models • Refine groundwater model estimates of recharge to the Pine Valley aquifer (R_{pv}), which are sensitive to these model inputs
General	Collect precipitation data. Install/ reactivate rain gages within Pine Valley HA in mountain and valley areas,	• Enable monitoring of current precipitation conditions in an area that currently has no active stations in the Remote Automatic Weather Station network [28]. • Refine average annual precipitation and recharge estimates
Mountain Springs in Pine Valley HA	Monitor current spring discharge.	• Establish baseline spring flows and natural range of variability • Inform evaluation and monitoring of potential PVWSP impacts to mountain springs.

REFERENCES

[1] V. M. Heilweil and L. E. Brooks, “Conceptual Model of the Great Basin Carbonate and Alluvial Aquifer System,” U.S. Geological Survey Scientific Investigations Report 2010–5193, 2011. [Online]. Available: https://pubs.usgs.gov/sir/2010/5193/

[2] J. R. Harrill, J. S. Gates, and J. M. Thomas, “Major ground-water flow systems in the Great Basin region of Nevada, Utah, and adjacent states,” U.S. Geological Survey, 694–C, 1988. doi: 10.3133/ha694C.

[3] A. L. Flint and L. E. Flint, “Application of the Basin Characterization Model to Estimate In-Place Recharge and Runoff Potential in the Basin and Range Carbonate-Rock Aquifer System, White Pine County, Nevada, and Adjacent Areas in Nevada and Utah,” U.S. Geological Survey Scientific Investigations Report 2007–5099, 2007. [Online]. Available: https://pubs.usgs.gov/sir/2007/5099/

[4] L. E. Brooks, M. D. Masbruch, D. S. Sweetkind, and S. G. Buto, “Steady-state numerical groundwater flow model of the Great Basin carbonate and alluvial aquifer system,” U.S. Geological Survey, 2014–5213, 2014. doi: 10.3133/sir20145213.

[5] L. E. Brooks, “Groundwater model of the Great Basin carbonate and alluvial aquifer system version 3.0: Incorporating revisions in southwestern Utah and east central Nevada,” U.S. Geological Survey, 2017–5072, 2017. doi: 10.3133/sir20175072.

[6] Formation Environmental, “Groundwater Resources Impact Assessment. Pine Valley Water Supply Project, Iron and Beaver Counties, Utah,” Prepared for Transcon Environmental and Central Iron County Water Conservancy District on behalf of Bureau of Land Management, 2021.

[7] “USGS Water Data for the Nation.” Accessed: June 23, 2025. [Online]. Available: https://waterdata.usgs.gov/nwis

[8] C. Daly et al., “Physiographically sensitive mapping of climatological temperature and precipitation across the conterminous United States,” Int. J. Climatol., vol. 28, no. 15, pp. 2031–2064, 2008, doi: 10.1002/joc.1688.

[9] J. Stephens, “Hydrologic Reconnaissance of the Pine Valley Drainage Basin, Millard, Beaver, and Iron Counties, Utah,” State of Utah Department of Natural Resources, Technical Publication No. 51, 1976. [Online]. Available: https://pubs.er.usgs.gov/publication/70042823

[10] P. M. Gardner, Marston, Thomas M., S. G. Buto, and L. E. Brooks, “Hydrogeologic and Geochemical Characterization of Groundwater Resources in Pine and Wah Wah Valleys, Iron, Beaver, and Millard Counties, Utah,” U.S. Geological Survey Scientific Investigations Report 2019–5139, 2020. [Online]. Available: https://pubs.usgs.gov/sir/2019/5139/sir20195139.pdf

[11] T. E. Eakin and others, “Contributions to the hydrology of eastern Nevada,” Nevada State Engineer Water Resources Bulletin 12, 1951.

[12] J. W. Hood and K. M. Waddell, “Hydrologic reconnaissance of Skull Valley, Tooele County, Utah,” Utah Department of Natural Resources Technical Publication 18, 1968.

[13] G. B. Maxey and T. E. Eakin, “Ground water in White River Valley, White Pine, Nye, and Lincoln Counties, Nevada,” Nevada State Engineer, Water Resources Bulletin 8, 1949. [Online]. Available: www.nrc.gov/docs/ML0331/ML033140348.pdf

[14] “Elevation Derivatives for National Applications (EDNA) | U.S. Geological Survey.” Accessed: May 30, 2025. [Online]. Available: https://www.usgs.gov/special-topics/elevation-derivatives-for-national-applications

[15] “STATSGO soil characteristics for the conterminous United States | U.S. Geological Survey.” Accessed: May 30, 2025. [Online]. Available: https://www.usgs.gov/publications/statsgo-soil-characteristics-conterminous-united-states

[16] G. S. Campbell, “Soil physics with BASIC: Transport models for soil plant systems,” in Developments in Soil Science, vol. 14, Amsterdam: Elsevier, 1985, p. 150 p.

[17] C. H. B. Priestley and R. J. Taylor, “On the Assessment of Surface Heat Flux and Evaporation

Using Large-Scale Parameters," Mon. Weather Rev., vol. 100, pp. 81–92, Feb. 1972.

[18] "Land Cover Data Overview | U.S. Geological Survey." Accessed: May 30, 2025. [Online]. Available: https://www.usgs.gov/programs/gap-analysis-project/science/land-cover-data-overview

[19] J. D. Lundquist and A. L. Flint, "2004 onset of snowmelt and streamflow: How shading and the solar equinox may affect spring runoff timing in a warmer world," J. Hydrometeorol., vol. 7, p. 1,199-1,217, 2006.

[20] N. Earth Science Data Systems, "Land Processes Distributed Active Archive Center | NASA Earthdata." Accessed: July 31, 2025. [Online]. Available: https://www.earthdata.nasa.gov/centers/lp-daac

[21] J. C. Stephens, "Hydrologic Reconnaissance of the Wah Wah Valley Drainage Basin, Millard and Beaver Counties, Utah," State of Utah Department of Natural Resources, Technical Publication No. 47, 1974. [Online]. Available: https://pubs.usgs.gov/publication/70043778

[22] H. H. Cooper and C. E. Jacob, "A generalized graphical method for evaluating formation constants and summarizing well-field history," Eos Trans. Am. Geophys. Union, vol. 27, no. 4, pp. 526–534, 1946, doi: 10.1029/TR027i004p00526.

[23] Roux Associates, Inc., "Technical memorandum r.e. groundwater impacts of the proposed Pine Valley Water Supply Project, Utah on Nevada groundwater basins with a Focus on Snake Valley, Nevada & Utah," Sept. 2021.

[24] U.S. Bureau of Land Management, "Pine Valley Water Supply Project Draft Environmental Impact Statement," DOI-BLM-UT-C010-2020-0012-EIS, Jan. 2022. [Online]. Available: https://eplanning.blm.gov/public_projects/1503915/200379940/20052653/250058836/Revised%20DOI-BLM-UT-C010-2020-0012-EIS_Public%20Comment.pdf

[25] D. J. McEvoy, J. F. Mejia, and J. L. Huntington, "Use of an Observation Network in the Great Basin to Evaluate Gridded Climate Data," J. Hydrometeorol., vol. 15, pp. 1913–1931, 2014.

[26] Roux Associates, Inc., "Technical memorandum r.e. comments regarding the Pine Valley Water Project DEIS and associated documents.," Mar. 2022.

[27] M. D. Masbruch, P. M. Gardner, and L. E. Brooks, "Hydrology and numerical simulation of groundwater movement and heat transport in Snake Valley and surrounding areas, Juab, Miller, and Beaver Counties, Utah, and White Pine and Lincoln Counties, Nevada," U.S. Geological Survey, 2014–5103, 2014. doi: 10.3133/sir20145103.

[28] "Utah Remote Automated Weather Station Data." Accessed: Nov. 11, 2025. [Online]. Available: https://raws.dri.edu/utF.htm

Appendix A: *Detailed overview table of Pine Valley area groundwater studies*

Study	Focus Area	Study Objectives	Type of Study	Recharge Estimation Method	Model Name and Software	Average Annual Recharge Estimate(s), in KAFY	Assumptions/ Limitations
Stephens 1976	Pine Valley (~730 sq. mi.)	Describe hydrology; assess potential for water development in area	Conceptual/ Empirical	Empirical method (Eakin and others 1951, Hood and Waddell 1968) that applies distinct rechage percentages to mapped precipitation and geology zones.	n/a	“Total recharge (R_i): 21, reported in Table 4 Recharge to valley aquifer (R_{pv}): 11, reported on p.21”	Assumes a 1 ft/yr ETm rate w/no supporting data.Assumes 5 gal/min average spring discharge rate but individual measurement data are variable. Assumes Rww=3 KAFY w/no explanation of how recharge in that calculation subarea was split between Pine and Wah Wah valleys.
Heilweil and Brooks 2011	Entire ~110,000 sq.mi .Great Basin Carbonate & Alluvial Aquifer System	Better assess GBCAAS groundwater availability	Conceptual/ Regional Water Balance Accounting Model	Distributed-parameter water balance accounting model that uses spatial data sets (soils, vegetation, geology etc.) and monthly climate data inputs to calculate recharge on a 270-m grid.	Basin Characterization Model (Flint and Flint 2007). Runs using Fortran code.	Total recharge (R_i): 27. Reported in Table A4-1.	Sensitivity analysis results suggest recharge estimates have uncertainty of ± 50%. Model assumes recharge occurs within a monthly time step but groundwater travel time may be much longer in some places. Geologic maps used to determine hydraulic conductivity are low resolution (1:500,000) and may not represent local conditions well.
Brooks et al. 2014	Entire ~110,000 sq.mi. Great Basin Carbonate & Alluvial Aquifer System	Test ability to model Heilweil & Brooks 2011 conceptual data; see if model can match observed groundwater values; assess regional groundwater availability	Steady-state regional numerical groundwater flow model	Numerical groundwater flow simulation using reasonable input parameters to generate estimates that provide a reasonable match to observed groundwater levels and discharge rates.	GBCAAS 1.0; MODFLOW-2005; Drain Package used to simulate ETg	Total recharge (R_i): 24. Reported in Table A3-2.	Model is regional-scale and not intended to guide or simulate effects of local-scale water management decisions. Hydrogeologic data and calibration data availability is very limited, particularly in some portions of the study area. 1-mi model grid size means important local-scale features may not be represented.
Brooks 2017	Southern GSL Desert and Sevier Lake systems; incorporates new information for Pine, Wah Wah, and Parowan HAs; model includes entire GBCAAS	Revise the GBCAAS model to incorporate updated information for model refinement focus area; use model to predict effects of proposed pipeline projects	Local updates to regional numerical groundwater flow model; includes both steady-state and transient simulations	Numerical groundwater flow simulation using locally-updated calibration data	GBCAAS 3.0; MODFLOW-LGR. Evapotranspiration Package used to simulate ETg	Recharge to valley aquifer (R_{pv}): 11. Reported in Table 8.	Model is scaled to the focus area and not meant to predict effects at the individual grid-cell level. Hydrogeologic data and calibration data availability is limited, particularly in some portions of the study area. 1-mi model grid size means important local-scale features may not be represented. Recharge estimates are only relevant for valley aquifer, not mountains.
Gardner 2020	Pine and Wah Wah Valleys (~1,330 sq.mi. area). Also includes research on groundwater discharge areas in Tule Valley and Sevier Lake	Support decision making related to proposed pipeline projects by providing refined hydrogeology information to inform Brooks (2017) GBCAAS model updates	Investigative data collection and analysis	n/a. Research for this study provided input into the Brooks 2017 moedling estimates.	n/a	n/a (reports Brooks 2017 estimate)	Assumes Sevier Lake playa is disconnected from regional groundwater based on limited sampling done in 2012-2013. States that Tule Valley and Sevier Lake ETg estimates have 35% uncertainty.
Formation 2021	Pine and Wah Wah Valleys and surrounding HAs (Snake Valley, Tule Valley, Sevier Desert, Milford, Beryl-Enterprise). The report also presents information for a smaller ~4,800 sq. mi "Focused Model Area" and a still smaller "Area of Project Effect". Model includes entire GBCAAS.	Provide updated hydrogeologic information about Pine Valley and develop a refined groundwater flow model to help assess groundwater-related impacts of the proposed Pine Valley Water Supply Project.	Impact assessemnt/ investigative data compilation and analysis/ numerical groundwater flow model	Subtraction of average annual evapotranspiration estimate (based on review of 10 years of Landsat imagery and supplemental weather station data) from average annual precipitation estimate (based on averaging weater station data).	GBCAAS-PV; MODFLOW-LGR. (child model that uses GBCAAS 3.0 as a parent model)	“Net recharge (R_n): 17.7, reported in Table 3-18. Recharge to valley aquifer (R_{pv}): 14.7, reported in Table 3-19.”	Model is limited by uncertainties due to limited data availability, particularly with respect to aquifer properties/ pumping information. Impacts of the PVWSP were predicted assuming 50 years of pumping followed by 200 to 450 years of recovery. Uses Stephens' 1976 assumption that Rww=3 KAFY. Model assumes Wah Wah Springs and Clay Spring are the only springs connected to the regional valley aquifer and that other springs are perched.

Study	Grid/ Cell Size	Temporal Approach	Model Calibration Data Used	Average Annual Precipitation Estimate (in KAFY) and Methods	Average Annual Wah Wah Springs Discharge Estimate	Recommended Additional Data Collection
Stephens 1976	n/a	n/a	n/a	410. U.S. Weather Bureau normal annual precipitation isohyets for 1931-1960.	500 gallons/minute (807 AFY) (Stephens 1974)	Drilling wells in southern portions of the valley and collecting water level, water quality, and geologic data; Drilling in the mountains of the southern Needle Range to identify and map perched groundwater zones; Investigating water quality variability (p.22)
Heilweil and Brooks 2011	270-m (0.17-mi.) grid	Monthly calculations averaged over the 1940-2006 time period to generate annual estimates for individual HAs.	California and Arizona ET data; MODIS snowcover data; runoff estimates from streamflow gage data in 44 HAs (none in Pine Valley HA);	12 inches/year (472 KAFY). 4 km resolution gridded PRISM precipitation data resampled to a 270-m grid and averaged for 1971-2000.	n/a	"Additional water-level data from deep wells are needed to confirm the extent of regional mounding beneath mountain blocks..." (p.67). "Additional mountain stream and spring discharge measurements are needed to refine these values [for total est. Q to mtn streams and springs]...Additional seepage studies along streams and canals, and deep percolation studies of irrigation return flow are needed to improve these estimates [of recharge from irrigated areas].." (p.118)
Brooks et al. 2014	1-mi grid. 8 vertical layers.	Steady state model. Represents pre-groundwater development conditions. Outputs annual estimates.	Observed water levels in wells and observed discharge via ETg, springs, and streams	n/a	86,400 cubic ft/day (724 AFY). Reported in Table A1-2. Table	"The model parameters are more uncertain in areas with limited observation data, and new data could indicate that revisions in the model are needed in those areas." p.85 "An appropriate use of this information would be by using differences in the simulated and conceptual water budgets to guide data collection in future, more detailed studies."p.104
Brooks 2017	1-mi grid. 8 vertical layers.	Includes both steady-state and transient simulations. Transient simulation provides annual projections for 14 stress periods totaling 5,000 years.	Newer water level observations (including lower levels on west side Sevier Lake) and newer ETg estimates (including a lower Sevier Desert discharge estimate due to playa geochemistry data that suggest no ETg discharges to Seveir Lake playa.)	n/a	748 AFY (reported in Table 1-6)	"The model...can be used to guide data collection of greatest use in reducing prediction uncertainty. The model can be used less formally to guide data collection by consideration of zonation and parameter values that were needed to achieve calibration in select areas and what data could be collected to verify or dispute the model parameters." p.60
Gardner 2020	n/a	n/a	n/a	510. Gridded PRISM precipitation data averaged for 1981-2010.	2.2 cfs (1600 AFY, measured in early 2016; reported on p.13)	no specific recommendations found in document
Formation 2021	0.2-mi grid, 16 vertical layers	Model calibrated using a 1,000 year equilibuium period to represent steady-state conditions. Transient predictive model uses one-year time steps for a 50-yr pumping/450-yr recovery scenario.	Calibrated to match observations of 92 water levels, 2 spring discharges, and 8 ETg estimates. Cell recharge and hydraulic conductivity parameters adjusted to avoid mounding and match updated (larger) recharge estimates relative to GBCAAS 3.0	388. Average of 6 weather stations in/near Pine Valley over their varying periods of record.	1,800 AFY, based on Gardner et al. 2020 measurement plus 200 AF of estimated average ET.	p. 5 lists data gaps. Chapter 6 provides monitoring rec's