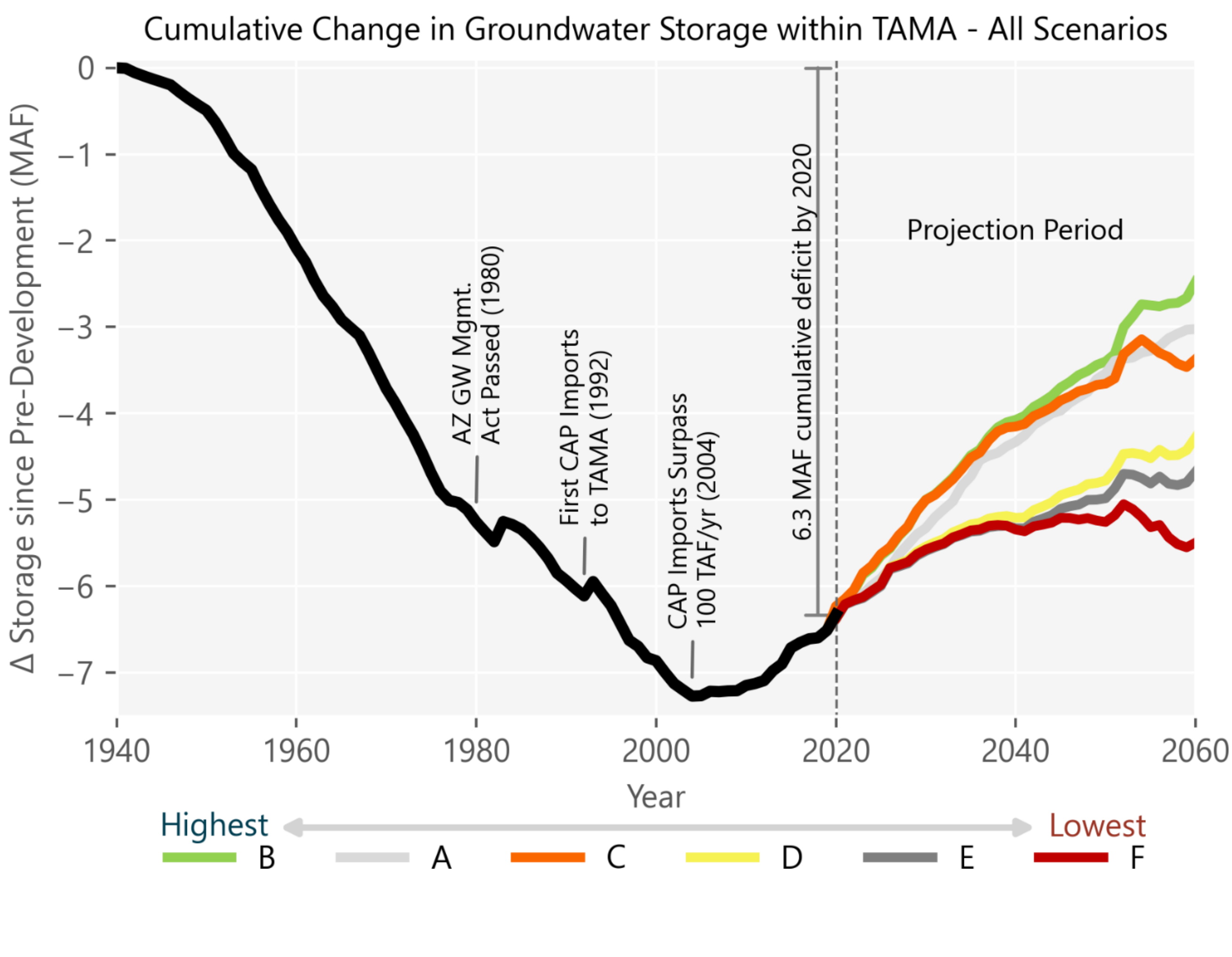
BUREAU OF RECLAMATION

Lower Santa Cruz River Basin Study Groundwater Analysis

Technical Memorandum ENV-2021-64



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

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On the Cover: Simulated change in groundwater storage by Basin Study supply-demand scenario

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Technical Service Center, Denver, Colorado
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Lower Santa Cruz River Basin Study Hydroclimate Analysis

Prepared for:

Phoenix Area Office
Lower Colorado Region
Bureau of Reclamation

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Acronyms and Abbreviations

ADWR	Arizona Department of Water Resources
afy	Acre-feet per year
AMA	Active Management Area
BAS	MODFLOW Basic Package
CAP	Central Arizona Project
CAP:SAM	Central Arizona Project Service Area Model
CAVSARP	Central Avra Valley Storage and Recovery Project
CDF	Cumulative probability distribution function
CDO	Cañada del Oro
cfs	cubic feet per second
CHD	MODFLOW Time-Variant Specified-Head Package
COOP	Cooperative Observation Network
DIS	MODFLOW Discretization Package
EVT	MODFLOW Evapotranspiration Package
FCAP	FICO CAP Line, LLC
FICO	Farmers Investment Company
GCM	Global Circulation Model
GHG	Greenhouse Gas
GIS	Geographic Information System
GSF	Groundwater Savings Facility
HD	Hybrid-delta
IGFR	Irrigation Grandfathered Right
K	Hydraulic conductivity
LSCR	Lower Santa Cruz River
M&I	Municipal and Industrial
MAF	million acre-feet
MGD	million gallons per day
mi	mile
MODFLOW	USGS MODular finite-difference groundwater FLOw modeling code
NWT	Newton formulation of MODFLOW

PAMA	Pinal Active Management Area
PCRFCD	Pima County Regional Flood Control District
RCH	MODFLOW Recharge Package
RCP	Representative Concentration Pathways
Reclamation	Bureau of Reclamation
Sac-SMA	Sacramento Soil Moisture Accounting
SAVSARP	Southern Avra Valley Storage and Recovery Project
SCAMA	Santa Cruz Active Management Area
SCR	Santa Cruz River
S-D	Supply-Demand
SECURE	Science and Engineering to Comprehensively Understand and Responsively Enhance
SHARP	Southeast Houghton Area Recharge Project
Study	Lower Santa Cruz River Basin Study
TAF	thousand acre-feet
TAMA	Tucson Active Management Area
UPW	MODFLOW Upstream Weighting (Groundwater Flow) Package
USF	Underground Storage Facilities
USGS	United States Geological Survey
WaterSMART	Sustain and Manage America's Resources for Tomorrow
WEL	MODFLOW Well Package
WRF	Water Reclamation Facility
yr	year

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Executive Summary

This Technical Memorandum describes the groundwater modeling portion of the Lower Santa Cruz River Basin Study (Study). The Study aims to identify where physical water resources are needed to mitigate supply-demand imbalances due to climate change and other factors, and to develop strategies to improve water reliability for municipal, industrial, agricultural, and environmental sectors in the Lower Santa Cruz River (LSCR) Basin. The LSCR Basin Study area is focused within the Tucson Active Management Area (TAMA; Figure ES-1) as defined by the Arizona Department of Water Resources (ADWR).

The Study uses a scenario planning approach to evaluate a range of plausible water supply and demand projections between 2020 to 2060. The Study Project Team developed six supply-demand (S-D) scenarios that reflect the insight of local partners into water resource futures for the Study area.

This groundwater modeling portion of the Study relies on previous efforts including: development and calibration of the TAMA groundwater flow model by ADWR (Mason & Hipke, 2013; the active TAMA Model domain is shown in Figure ES-1), projections of future water supplies and demands by the Central Arizona Water Conservation District (commonly referred to as the Central Arizona Project, or CAP; CAP, 2021), recharge modeling provided by CAP (Montgomery and Associates, 2020), and projections of natural streamflow by the Bureau of Reclamation (Reclamation, 2021).

The six S-D scenarios developed by the Study Project Team are pairwise combinations of scenarios related to (1) the climate within the Lower Santa Cruz River Basin and the resulting natural recharge ("current", "best-case", and "worse-case") and (2) projected demand growth and pattern ("slow/compact", "medium/official", and "rapid/outward"). The "best-case" and "worse-case" climate scenarios are informed by results from global circulation models (GCMs) for greenhouse gas atmospheric concentration scenarios (i.e., Representative Concentration Pathways [RCP]) 4.5 and 8.5, respectively. For the "current" climate scenario, historic values were repeated over the projection period.

Table ES-1. Basin Study supply-demand scenario matrix. In general, water resource risk increases from the lower-left towards the upper-right.

		Demand Growth		
		Slow, Compact	Medium, Official	Rapid, Outward
Climate	Worse Case	D	E	F
	Best Case	B	Higher Risk	C
	Current Climate		A	

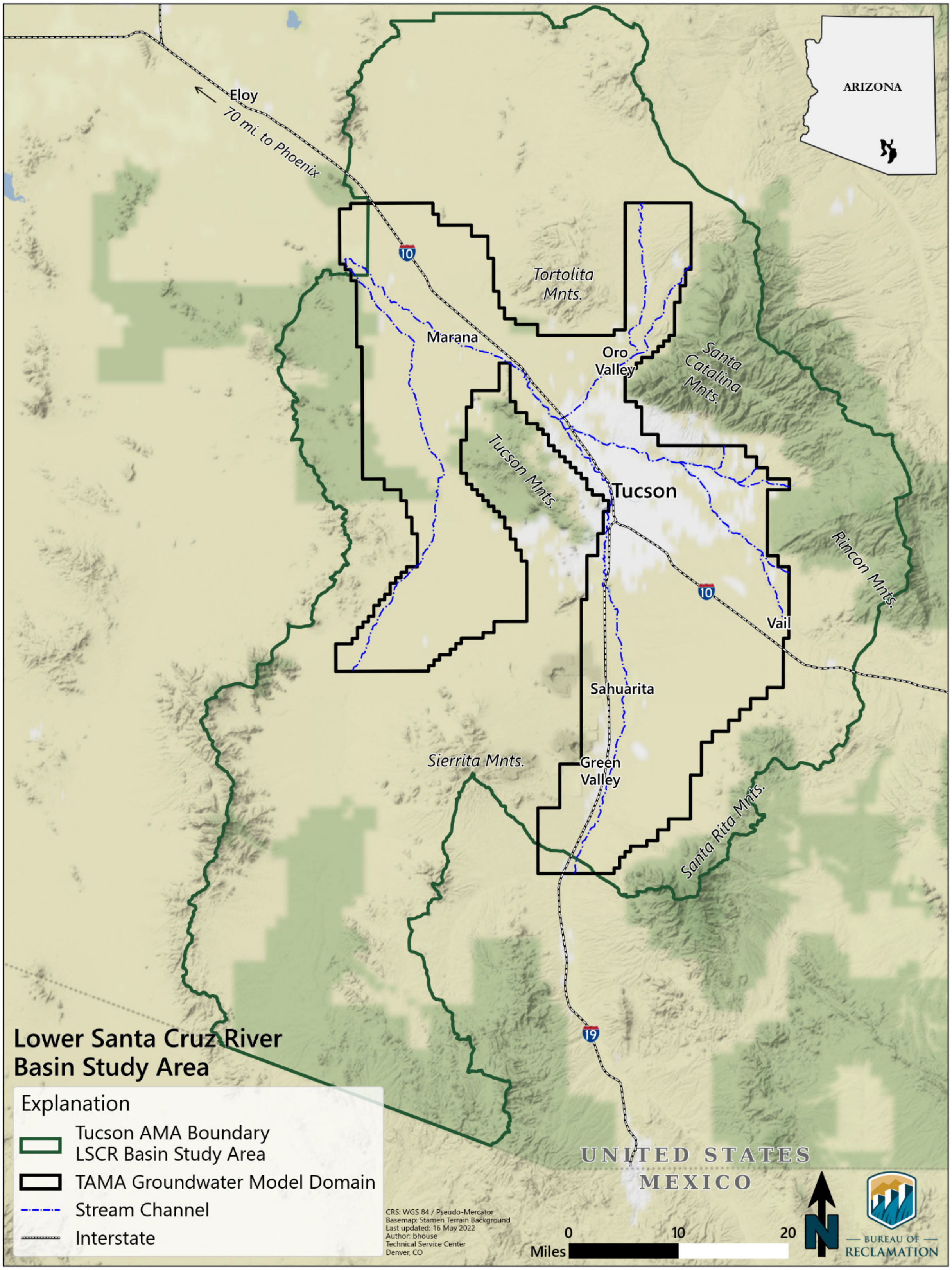

Figure ES-1. Lower Santa Cruz River Basin Study Area and modeling boundaries.

Demand growth scenarios relate to both the rate ("slow", "medium", or "rapid") and pattern ("compact", "official", or "outward") of growth. These demand growth scenarios also incorporated a range of shortages of Colorado River water imported via the CAP. More information on the demand growth scenarios is available in Appendix C of the *Lower Santa Cruz River Basin Study: Supply and Demand Assessment* report (CAP, 2021).

Table ES-1 presents a matrix of these climate and demand growth scenarios and identifiers (A-F) associated with each pairwise combination. In general, risk to water resources and the environment increases from the lower-left to the upper-right with B representing a lower risk and F a higher risk.

The enactment of Arizona's Groundwater Management Act in 1980 created several Active Management Areas (AMAs) in regions of Arizona with long-term groundwater storage declines—including the TAMA (LSCR Basin). The TAMA began receiving imports of Colorado River water via the CAP in 1992 with completion of the CAP. Importation of CAP water to the TAMA steadily increased until 2007 and has plateaued since. Prior to these imports, the TAMA relied almost exclusively on groundwater to meet its water demands. This led to significant groundwater overdraft and a declining groundwater table.

The TAMA's management goal is to achieve long-term "safe yield" by 2025 (ADWR, 2016). Safe-yield is defined under Arizona Revised Statutes Title 45 Section 561 as:

> "[A] groundwater management goal which attempts to achieve and thereafter maintain a long-term balance between the annual amount of groundwater withdrawn in an active management area and the annual amount of natural and artificial recharge in the active management area."

The TAMA Groundwater Flow Model (TAMA Model) was used to evaluate impacts of the Study S-D scenarios and proposed adaptation strategies on groundwater resources within the Study area over the projection period, 2020-2060 (Mason & Hipke, 2013). It uses version 1.0.7 of the U.S. Geological Survey's (USGS) groundwater modeling code MODFLOW-NWT (Niswonger et. al., 2011). ADWR maintains the TAMA Model to support water resource planning and management in the TAMA, with the goal of being able to "evaluate relative changes within the regional system" (Mason & Hipke, 2013).

Groundwater pumping projections for each of the S-D scenarios were developed by a subset of the Project Team and CAP. Municipal, industrial and agricultural demands were translated into input files to the TAMA Model for each of the simulated S-D scenarios.

Simulated inflows to the groundwater model (in descending order of magnitude at the end of the modeled period) occur from:

- artificial recharge of CAP (Colorado River) water and reclaimed water[1]
- infiltration of natural and reclaimed water-derived streamflow
- mountain front recharge
- underflow from adjacent basins

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[1] Reclaimed water, as defined by Arizona law, is water that has been treated or processed by a water reclamation facility.

- agricultural deep percolation
- seepage from mine tailings ponds.

Simulated outflows from the groundwater model (in descending order of magnitude at the end of the modeled period) occur from:

- municipal pumping
- agricultural pumping
- mining pumping
- underflow to an adjacent basin
- industrial pumping
- evapotranspiration.

Projections of Simulated Inflows

Inflows to the groundwater model over the projection period are summarized in Table ES-2, including the range of inflows from the various sources across all S-D scenarios and the MODFLOW package used to simulate each inflow. The rate columns (in thousands of acre-feet per year [TAF/yr]) provide insight into the impact of sources of inflow on the model results.

Table ES-2. Summary of TAMA Model inflows over the projection period and across all S-D scenarios. Development of each is described in the *Simulated Inflows* section of this Technical Memorandum.

Description	Rate (TAF/yr)			MODFLOW Package	Data Source(s)
	Min	Mean	Max		
Mountain Front Recharge*	-	28	-	RCH	Mason & Hipke (2013)
Underflow	27	28	29	WEL, CHD	Mason & Hipke (2013)
Mine Tailings Pond Seepage*	-	8	-	RCH	Mason & Hipke (2013)
Stream Channel Infiltration	54	121	382	RCH	Reclamation (2021), Mason & Hipke (2013), CAP (2021), Study Partners
Artificial Recharge Facilities	93	177	223	RCH	CAP (2021), Study Partners
Agricultural Deep Percolation	18	20	20	RCH	CAP (2021), Study Partners

*Inflow is constant over the projection period and across all S-D scenarios

The cumulative sum of groundwater inflows under each S-D scenario is shown in Figure ES-2. The apparent groupings of scenarios in Figure ES-2 highlight the impact of climate on inflows (Table ES-2). Cumulative inflows (recharge) under scenarios A, B, and C (current and best-case climates) are about 1.6 million acre-feet (MAF) greater over the projection period than under scenarios D, E, and F (worse-case climate). Differences in climate between the current and best-case scenarios and the worse-case scenario result in a difference in annual average recharge of about 40 TAF/yr over the projection period.

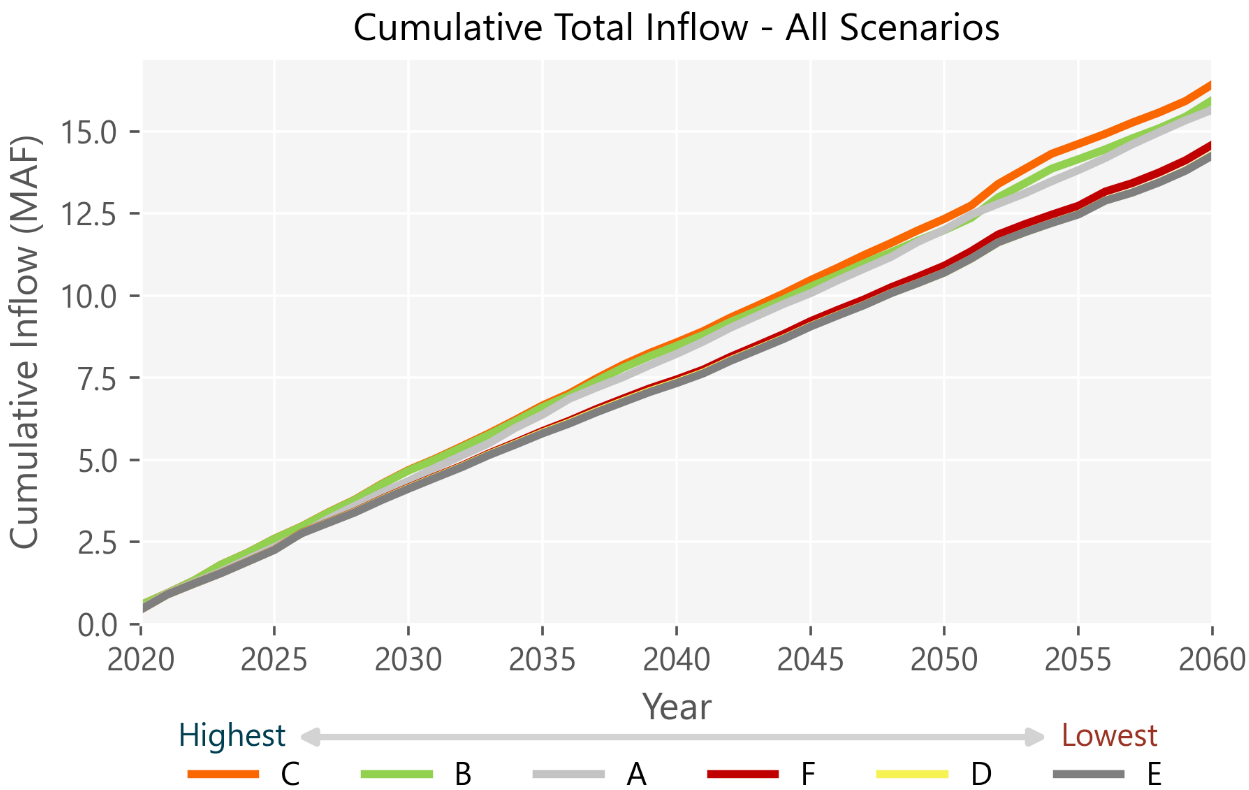

Figure ES-2. Cumulative sum of total annual simulated inflows to the TAMA groundwater model by S-D scenario.

Projections of Simulated Outflows

Outflows from the groundwater model over the projection period are summarized in Table ES-3, including the range of rates for each outflow across all S-D scenarios and the MODFLOW package that is used to simulate the outflow. The rate columns provide insight into the impact that each source of outflow has on the model results. Pumping accounts for an average of 92% of total outflows simulated from the TAMA Model over the projection period and across all S-D scenarios.

Table ES-3. Summary of groundwater model outflows over the projection period and across all S-D scenarios. Development of each is described in the section of this Technical Memorandum.

Description	Rate (TAF/yr)			MODFLOW Package	Data Source(s)
	Min	Mean	Max		
Evapotranspiration	0.4	4	16	EVT	Mason & Hipke (2013)
Underflow	17	20	26	CHD	Mason & Hipke (2013)
Pumping – Municipal	145	166	268	WEL	Mason & Hipke (2013), CAP (2021), Study Partners
Pumping – Ag	47	57	70	WEL	Mason & Hipke (2013), CAP (2021)
Pumping – Mining	29	34	46	WEL	Mason & Hipke (2013), Study Partners
Pumping – Industrial (Non-Mining)*	-	13	-	WEL	Mason & Hipke (2013)

*Outflow is constant over the projection period and across all S-D scenarios

Annual groundwater pumping for all sources is shown in Figure ES-3 for the projection period. For context, the historical simulated pumping is also shown. The rapid/outward demand growth projections (C and F) show significant increases over the projection period and, by 2060, reach rates similar to the peak abstraction period of the mid-1970s. All other S-D scenarios suggest only modest rises in pumping demands compared to the historical 1940-1960 period—with the lower risk scenario (B) being approximately constant. However, none of the projections suggest a decline in groundwater pumping.

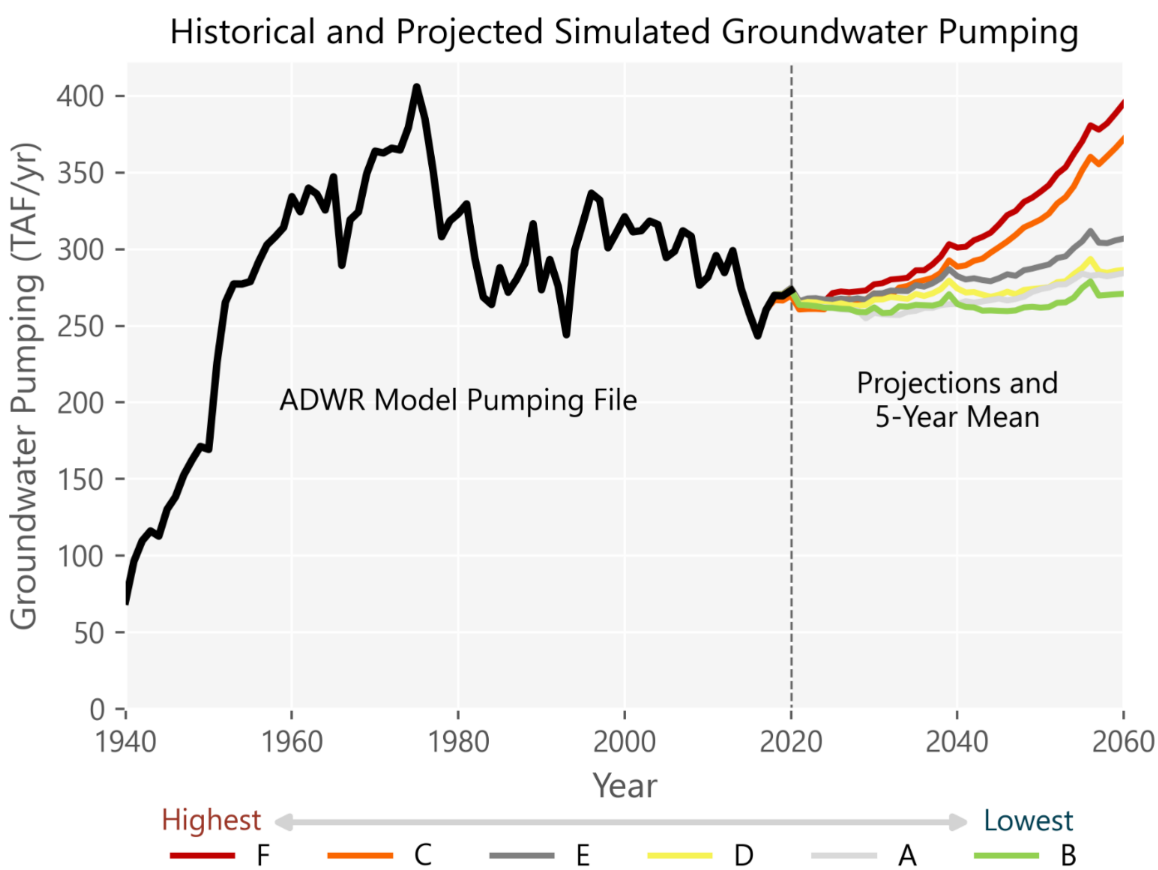

Figure ES-3. Historical and projected annual groundwater pumping simulated in the TAMA Model.

Summary: Results from All Supply-Demand Scenarios

Simulated changes in groundwater storage over the projection period under each S-D scenario are shown in the right portion of Figure ES-4. Projected changes in groundwater storage exhibit a general grouping by climate scenario. Groundwater storage increases for all S-D scenarios through the end of 2030s. By 2060 scenarios A, B, and C (current and best-case climates) result in a notably greater increase in groundwater storage than scenarios D, E, and F (worse-case climate). Separation between scenarios D, E, and F in the later portion of the projection period suggests that differences in demand growth have a more significant impact over time.

While the higher risk scenario (F) is generally in overdraft for the final 10-years of the projection period, all other S-D scenarios are generally in surplus (Figure ES-4). This result suggests that under the range of water supply and demand growth considered in the Study S-D scenarios, the LSCR Basin as a whole has increasing groundwater storage throughout most of the projection period. However, this result does not mean that groundwater storage increases in all areas of the LSCR Basin; some areas exhibit declines in groundwater storage while others experience increases.

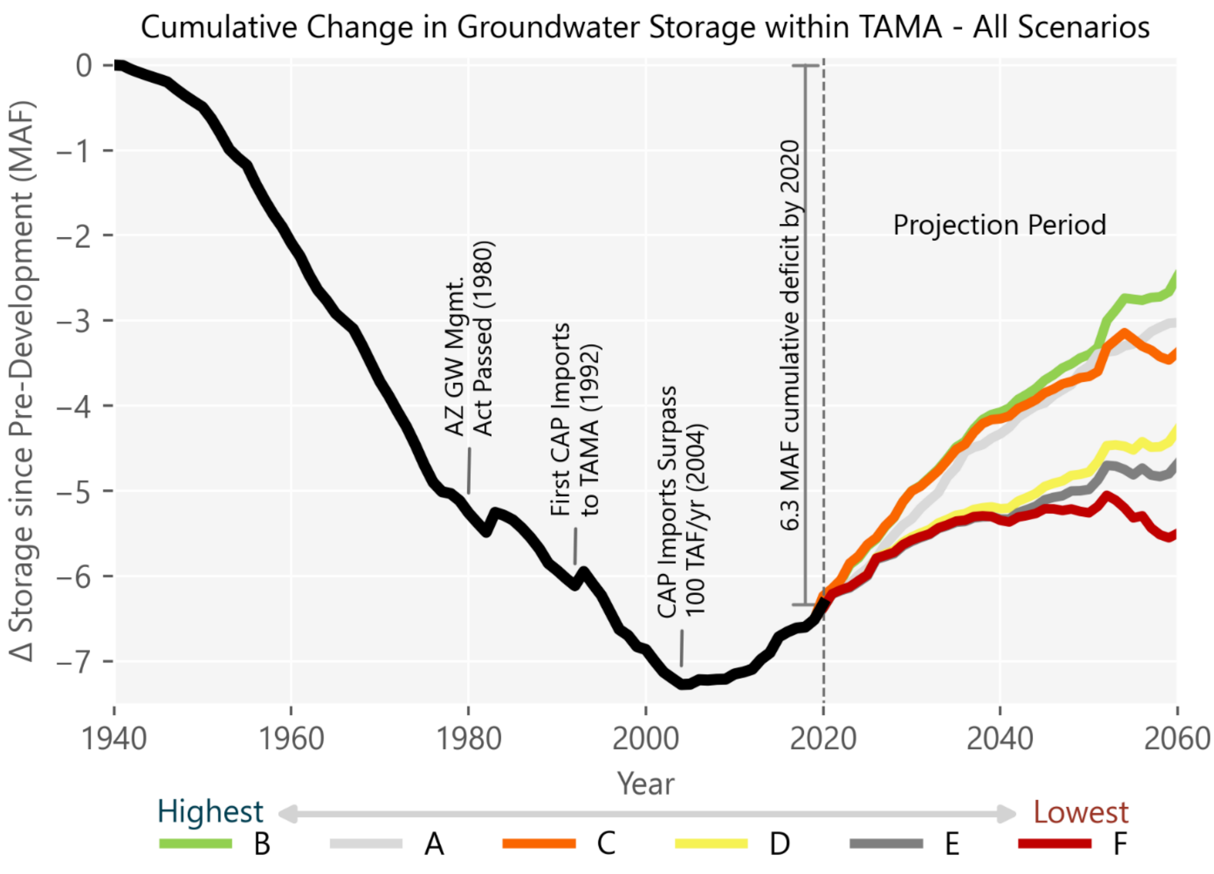

Figure ES-4. Simulated cumulative change in groundwater storage within the TAMA Model since pre-development (1940). Historical period is in black with results from Study S-D scenarios branching out at the start of the projection period (2020).

Maps of the simulated change in the groundwater table over the projection period—i.e., the difference in water table elevation between 2060 and 2020—provide insight into the spatial distribution of projected changes in groundwater heads and storage. Total hydraulic head of groundwater is a combination of both pressure from the weight of the water and the elevation of the water. The head at a point in an aquifer (in three-dimensions) is the elevation that water will rise to within a pipe screened or open to that point. For this broad-scale Study, groundwater head can generally be considered to be the elevation of the water table.

The spatial distribution of projected changes in groundwater heads under each S-D scenario is presented in Figure ES-5. The color scale is the same across all panels in Figure ES-5, with blue areas indicating an increase in groundwater levels and red areas indicating a decrease. All panels of Figure ES-5 show blue shading near and along the Santa Cruz River (SCR) northwest of Tucson, indicating a rise in groundwater levels in this portion of the LSCR Basin under all S-D scenarios. This is a result of increased discharge and infiltration of reclaimed water from two metropolitan Water Reclamation Facilities (WRFs) along the SCR.

Darker blue shading under scenarios B and C, compared to scenarios D, E, and F, indicate projected increases in streamflow in the Tanque Verde and Rillito Creek area under the best-case climate (Reclamation, 2021). Figure ES-5 also shows continued propagation of the groundwater mounds created by recharge at the Central Avra Valley Storage and Recovery Project (CAVSARP) and the Southern Avra Valley Storage and Recovery Project (SAVSARP) facilities in the Avra Valley subbasin under all S-D scenarios.

Areas of groundwater table rise related to new recharge facilities are also shown under all S-D scenarios. Three new facilities (two of which are operating as of 2022) are included in the projections. These are the Southeast Houghton Area Recharge Project (SHARP) to the east, Project RENEWS in the Green Valley area, and the Santa Cruz River Heritage Project in central Tucson. Recharge of reclaimed water from the Green Valley WRF also contributes to the rise in the Green Valley area across all S-D scenarios.

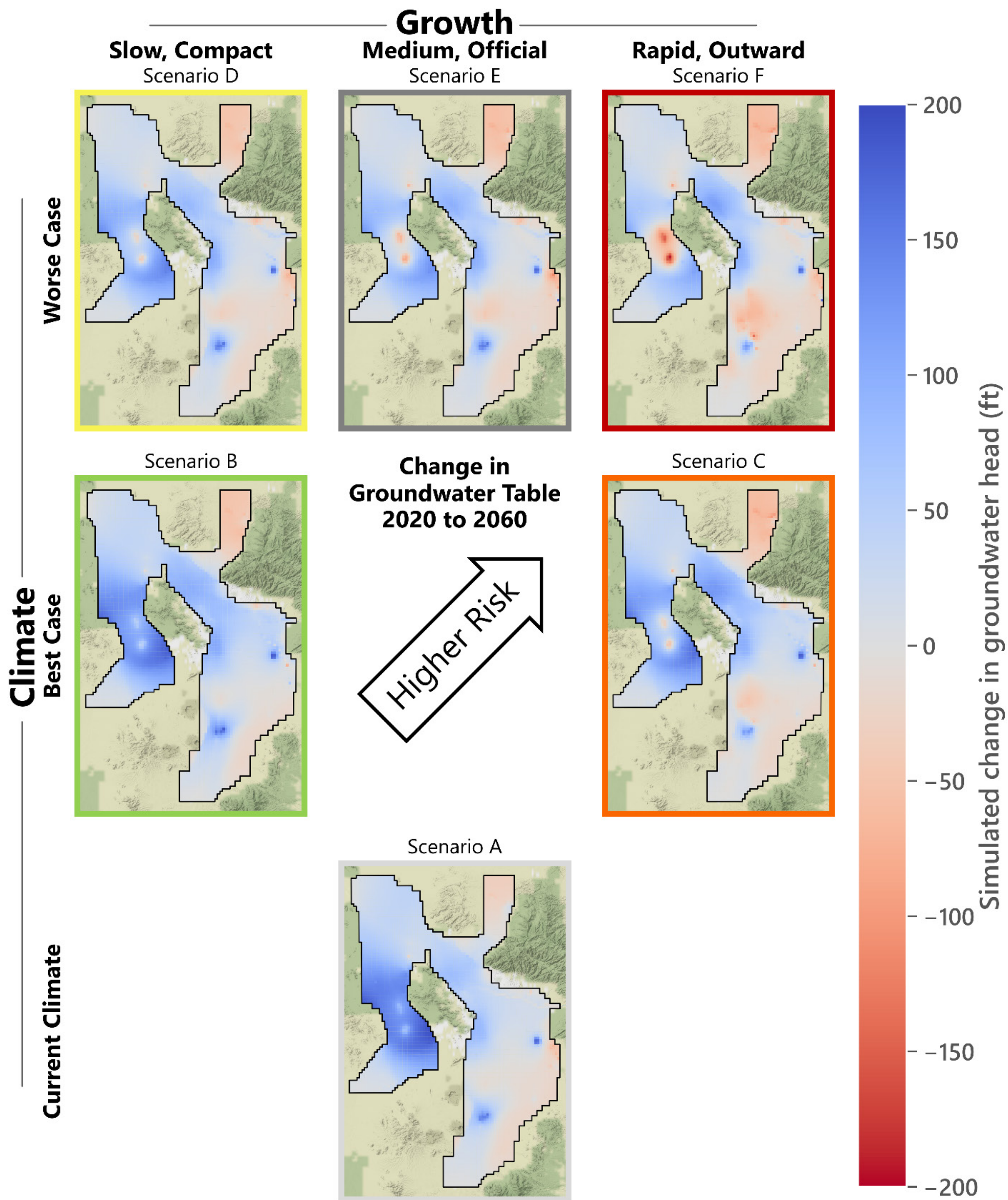

Figure ES-5. Change in simulated head by model cell over the projection period for each Study S-D scenario. Maps are positioned in the layout of Table ES-1. Color scale is shared between all maps.

Five adaptation strategies were simulated with the TAMA Model to evaluate the impact each would have on the groundwater table by the end of the projection period. Simulations were conducted as if a given adaptation strategy was implemented for the duration of the projection period (40 years). All simulations were conducted under scenario F, which reflects the higher risk to water resources for this Study. Results suggest that all five strategies simulated are effective at increasing the simulated groundwater table by at least a foot over large portions of the Study area. In generally, the greater the rate of recharge or pumping offset, the greater the benefit to groundwater table.

1. Introduction

The Bureau of Reclamation (Reclamation) conducts the Basin Study Program to evaluate future water supply and demand imbalances and develop strategies to address these imbalances. The Basin Study Program is part of the U.S. Department of the Interior WaterSMART (Sustain and Manage America's Resources for Tomorrow) Program[2], which addresses 21st-century water supply challenges such as population growth, increased competition for finite water supplies, and climate change.

Reclamation, in partnership with six local non-federal cost-share partners, began the Lower Santa Cruz River Basin Study (Study) in southeastern Arizona in 2016. Non-federal cost-share partners include the Southern Arizona Water Users Association, the Pima Association of Governments, the Cortaro-Marana Irrigation District, the Arizona Department of Water Resources (ADWR), the Central Arizona Water Conservation District (also known as the Central Arizona Project or CAP), and the University of Arizona.

As defined in the *Plan of Study* (Reclamation, 2016), the overarching goal of this Study is to identify where physical water resources are needed to mitigate supply-demand imbalances due to climate change and other factors and to develop strategies to improve water reliability for municipal, industrial, agricultural, and environmental sectors in the Lower Santa Cruz River Basin. In this Technical Memorandum, supply-demand imbalances will generally be referred to as “risk to water resources”. Low risk to water resources correlates with minimal need for adaptation, while high risk correlates to a greater need for adaptation. The future projection period for the Study is 2020 to 2060.

The Study area is focused within the Tucson Active Management Area (TAMA; Figure 1), as defined by ADWR. The Study uses a scenario planning approach to evaluate a range of future LSCR Basin-wide climate conditions, as well as a range of population growth rates and development patterns. Scenarios are based on projected climate conditions and a combination of population growth rate and development pattern (demand/growth) out to the 2060 planning horizon. For this Study, six scenarios with pairwise combinations of climate conditions and demand/growth were evaluated (scenarios are lettered A-F).

This Technical Memorandum describes the groundwater modeling portion of the Study and relies on previous efforts including: development and calibration of the TAMA groundwater flow model by ADWR (Mason & Hipke, 2013; the active TAMA Model domain is shown in Figure 1), projections of future water supplies and demands by CAP (CAP, 2021), recharge modeling provided by CAP (Montgomery and Associates, 2020) and projections of natural streamflow by Reclamation (Reclamation, 2021). CAP used the Central Arizona Project Service Area Model (CAP:SAM) to develop projections of most water supplies and demands within the Study area.

Projections of water supply and demand growth were translated into groundwater inflows and outflows for input into the TAMA groundwater flow model by Study Partners with expert

[2] https://www.usbr.gov/watersmart/

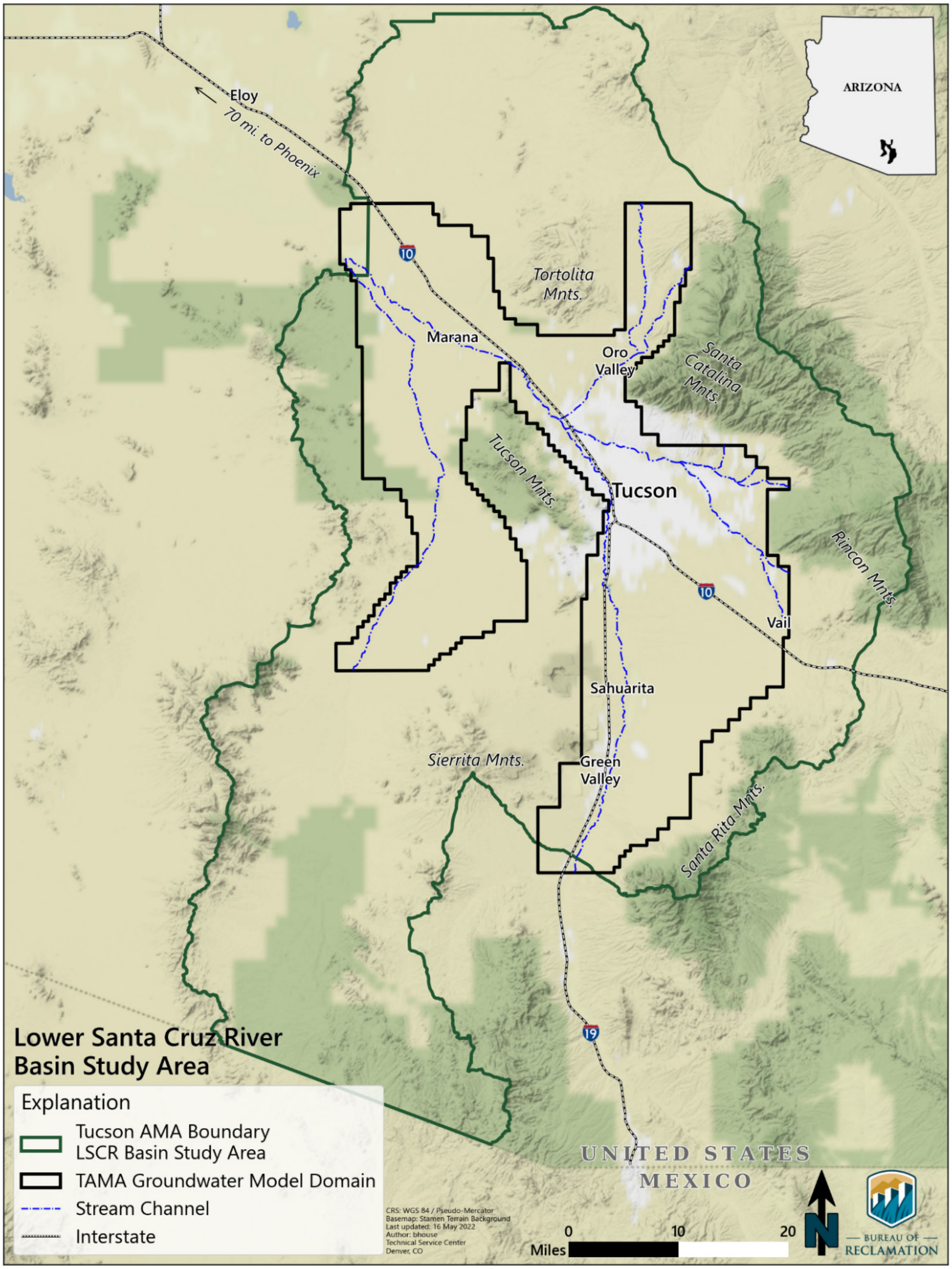

Figure 1. Lower Santa Cruz River Basin Study Area and the TAMA groundwater model boundary.

knowledge. Results from the groundwater model projection period (2020-2060) provide insight into the range of plausible future conditions for the groundwater resources in the Study area. Results were also used to inform adaptation strategies that address areas of supply-demand imbalances and declining groundwater heads/storage. Finally, five proposed adaptation strategies are simulated in the groundwater flow model to evaluate the impact each would have on the groundwater table by the end of the projection period.

1.1. Basin Study Background and Overview

The Basin Study Program is part of the U.S. Department of the Interior WaterSMART (Sustain and Manage America's Resources for Tomorrow) Program, which addresses 21st-century water supply challenges such as population growth, increased competition for finite water supplies, and climate change. The establishment of the WaterSMART Program addresses the authorities within the SECURE (Science and Engineering to Comprehensively Understand and Responsively Enhance) Water Act (Subtitle F of the Omnibus Public Land Management Act of 2009, Public Law 111-11), enacted into law on 30 March 2009. The SECURE Water Act provides authority for federal water and science agencies to work with state and local water managers to plan for climate change and other threats to water supplies, and to take action to secure water resources for the communities, economies, and ecosystems they support.

In 2009, Reclamation initiated the WaterSMART Basin Study Program to fund comprehensive studies that evaluate options for meeting future water demands within river basins in the West where imbalances in supply and demand exist or are projected. A Basin Study is conducted as a collaborative, cost-share partnership with non-Federal partners to: quantify current and future water supply and demand imbalances, assess the resulting risks to the basin resources, develop strategies to resolve those imbalances, and perform a trade-off analysis. In this technical memorandum, supply-demand imbalances will generally be referred to as “risk to water resources”. Low risk to water resources correlates with a lesser need for adaptation while high risk correlates to a greater need for adaptation.

The enactment of Arizona’s Groundwater Management Act in 1980 created several Active Management Areas (AMAs) in regions of Arizona with long-term groundwater storage declines. AMAs are subject to intensive water resource management by ADWR. The Study area coincides with the Tucson Active Management Area (TAMA) boundary (Figure 1). The TAMA’s management goal is to achieve long-term “safe-yield” by 2025 (ADWR, 2016). Safe-yield is defined under Arizona Revised Statutes Title 45 Section 561 as:

“[A] groundwater management goal which attempts to achieve and thereafter maintain a long-term balance between the annual amount of groundwater withdrawn in an active management area and the annual amount of natural and artificial recharge in the active management area.”By this statute, safe-yield is achieved on an AMA-wide basis. Early on, it was recognized that as safe-yield conditions were attained on an AMA-wide basis, some areas could be depleted, some areas of active recharge could be in surplus, and other areas could achieve a localized balance between the amount of water recharged and pumped (ADWR, 1999).

The Study Area began receiving imports of Colorado River water in 1992 with completion of the CAP—a series of canals and pipelines stretching over 360 miles (mi) from Lake Havasu, AZ and terminating just south of the San Xavier District of the Tohono O’odham Nation, within the Study Area. Importation of CAP water to the TAMA steadily increased through 2007 and has plateaued since. Prior to these imports, the TAMA relied almost exclusively on groundwater to meet its water demands. This led to significant groundwater overdraft and a declining groundwater table.

Municipal CAP water entitlements are either recharged into the aquifer for storage and recovered for treatment and use or substituted for groundwater that would otherwise be pumped by agriculture. In addition to CAP water deliveries, the region has seen a marked reduction in per capita water use, as well as declines in agricultural groundwater use. As a result, groundwater levels have rebounded in many areas, despite the population growing to over 1 million people in 2020. However, there are still local supply-demand imbalances within the Study area due to a lack of transmission infrastructure, a lack of recharge and recovery facilities in up-groundwater-gradient parts areas, and the cost of constructing new facilities.

The Study uses a scenario planning approach to evaluate a plausible range of projections of water supply and demand over the projection period—2020 to 2060. The Study Project Team developed six supply-demand (S-D) scenarios that reflect the insight of local partners regarding the range of water resource futures for the Study area (Figure 1). These include pairwise combination of three scenarios related to climate ("best-case", "current", and "worse-case") and three related to demand growth and pattern ("slow/compact", "medium/official", and "rapid/outward").

Climate scenarios generally correlate with water supply within the Study area. The "best-case" and "worse-case" climate scenarios for the Study area were developed using results from global circulation models (GCMs) for two greenhouse gas atmospheric concentration scenarios (i.e., Representative Concentration Pathways [RCP]) 4.5 and 8.5, respectively. The "best-case" and "worse-case" climate scenarios represent opposing ends of the spectrum of risk to water resources for the Study area. However, they do not describe the full extent of the possible range of impacts from changes in climate (i.e., "best-case" [*sic*] does not represent the best possible future nor "worse-case" the worst possible future).

A "current" climate scenario was also used to provide comparisons with products from other organizations that do not formally include the impacts of climate change in their projections of supply and demand. For the "current" climate scenario, historic values were repeated over the projection period.

The "best-case", "current", and "worse-case" climate scenarios for the Study area align with plausible sequences of shortages to imported Colorado River water supplies conveyed via the CAP. While the Study's specific climate scenarios were only modeled within the LSCR Basin (see *Lower Santa Cruz River Basin Study Hydroclimate Analysis* [Reclamation, 2021]), the CAP delivery supply sequences from CAP (2021; Figure 2) correspond to the same emissions levels: RCP 4.5, current climate, or RCP 8.5 levels of emissions.

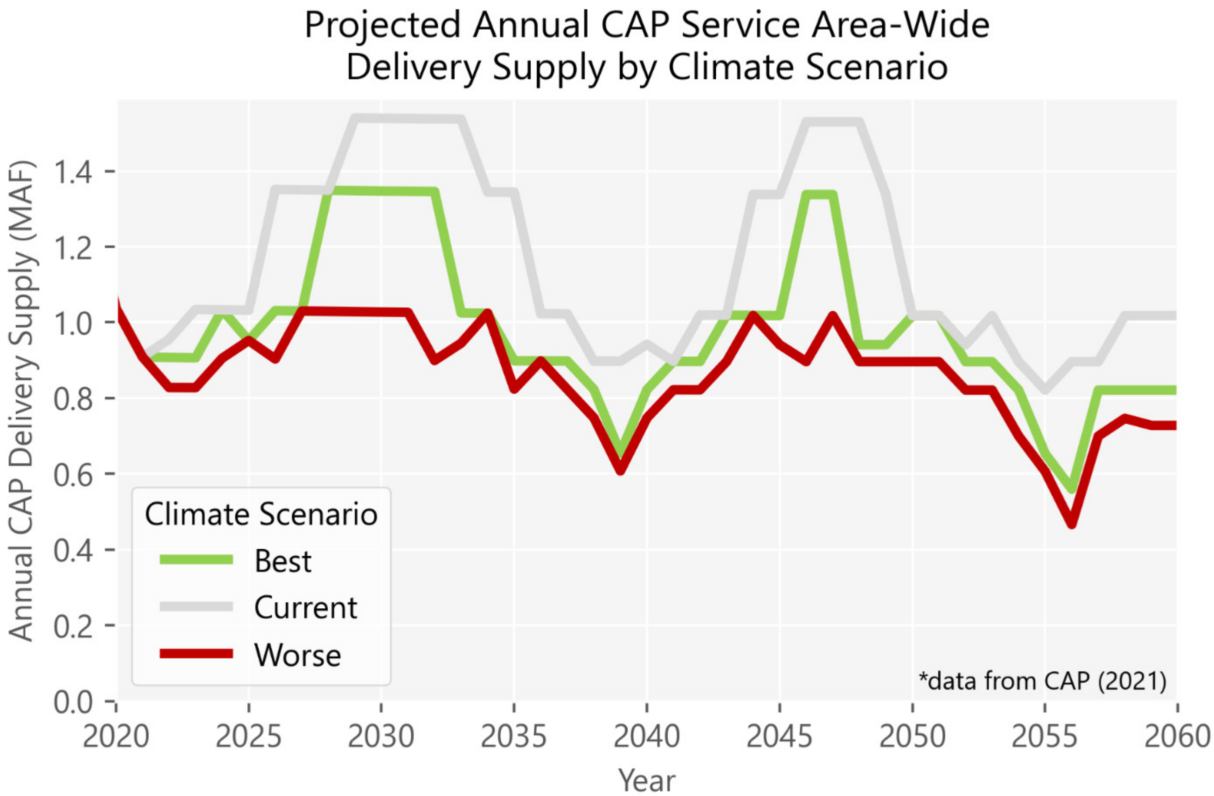

Figure 2. CAP (Colorado River water) service area-wide delivery supply by climate scenario. Data from CAP (2021).

Demand growth scenarios relate to both the rate ("slow", "medium", or "rapid") and pattern ("compact", "official", or "outward") of municipal and industrial growth. Detailed information on these scenarios can be found in Section 4 of the CAP Supply and Demand Assessment (2021).

Table 1 presents a matrix of these climate and demand growth scenarios and identifiers (A-F) associated with each pairwise combination. Based on Study Partner input, not all combinations of climate and demand growth were evaluated. In general, the risks to water resources and the environment increases from the lower-left to the upper-right with scenario B representing a lower and F a higher risk.

Table 1. Lower Santa Cruz River Basin Study supply-demand (S-D) scenario matrix

		Demand Growth		
		Slow, Compact	Medium, Official	Rapid, Outward
Climate	Worse Case	D	E	F
	Best Case	B	Higher Risk	C
	Current Climate		A	

1.2. TAMA Groundwater Flow Model

The TAMA Groundwater Flow Model (TAMA Model) was used to evaluate impacts of the S-D scenarios and proposed adaptation strategies on groundwater resources within the Study area over the projection period (2020-2060). The first groundwater models of the Tucson and Avra Valley basins were developed in 1972 using an electronic analog system (Anderson, 1972 and Moosburner, 1972). Since then, approximately five iterations of groundwater flow models have been developed for the Study area. The current version of the TAMA Model, which is used in this Study, was released by ADWR in 2013. It uses version 1.0.7 of the U.S. Geological Survey's (USGS) groundwater modeling code MODFLOW-NWT (Mason & Hipke, 2013; Niswonger et. al., 2011). ADWR maintains the TAMA Model to support water resource planning and management in the TAMA, with the goal of being able to "evaluate relative changes within the regional system" (Mason & Hipke, 2013).

The TAMA Model domain encompasses two main subbasins: the Avra Valley Subbasin to the west and the Upper Santa Cruz Subbasin to the east (Figure 3). The subbasins are separated by the Tucson Mountains. The model simulates groundwater conditions over the period 1940-2010 using an annual stress period (i.e., produces a simulated distribution of groundwater heads annually). General parameter ranges and characteristics of the model are summarized in Table 2. In general, hydraulic conductivities (K) are higher in the upper layers and near major streams and washes.

Simulated inflows to the groundwater model (in descending order of magnitude at the end of the modeled period) occur from:

- artificial recharge of CAP (Colorado River) water and reclaimed water
- infiltration of natural and reclaimed water-derived streamflow

- mountain front recharge
- underflow from adjacent basins
- agricultural deep percolation
- seepage from mine tailings ponds

Simulated outflows from the groundwater model(in descending order of magnitude at the end of the modeled period) occur from:

- municipal pumping
- agricultural pumping
- mining pumping
- underflow to an adjacent basin
- industrial pumping
- evapotranspiration

Prior to 1900, groundwater pumping within the TAMA was minimal and used for meeting domestic and stock animal demands (Mason & Bota, 2006). Agricultural development began in the early 1900s, with the first high capacity well installed in 1937. According to a number of groundwater modeling efforts, the TAMA groundwater system was, "still in a state of dynamic equilibrium until about 1940" (Mason & Bota, 2006)—where Mason & Bota defined dynamic equilibrium as, "long-term natural recharge balanced by long-term natural discharge" (2006). Simulated groundwater heads from 1940 (pre-development) indicate groundwater generally flows from south to north and out of the model domain in the northwest corner (Figure 3). This general flow pattern has not been altered with development.

Groundwater abstractions increased significantly from an estimated 70 thousand acre-feet per year (TAF/yr) in 1940 to a peak of over 400 TAF/yr in 1975 (Mason & Hipke 2013). Groundwater abstractions subsequently declined to approximately 280 TAF/yr in 2010–the final year of the TAMA Model simulation period. Groundwater pumping during much of this period far exceeded recharge, resulting in a near-continuous decline in groundwater storage from the mid-1940s to the mid-2000s. Mason & Hipke (2013) estimated that at its low in 2004, there had been a 6.8 million acre-foot (MAF) decline in groundwater storage within the model domain. The importation of Colorado River water via CAP had offset some pumping demands and supplied artificial recharge, resulting in minor groundwater storage recovery since the mid-2000s. The TAMA Model estimates that groundwater storage increased by approximately 0.2 MAF between 2004 and 2010 (Mason & Hipke, 2013).

There is an interim period between the end of the TAMA Model simulation period (2010) and the start of the Study projection period (2020). Updated MODFLOW Well package (WEL) and MODFLOW Recharge package (RCH) input files were provided by ADWR though 2017 (ADWR, 2019; ADWR, 2020a). WEL includes groundwater stresses from pumping and underflow from adjacent basins. RCH includes all sources of recharge to the groundwater system except underflow from adjacent basins. An interim period of 2018 to 2019 for the WEL and RCH remains before the start of the projection period in 2020. Actual pumping rates by well for these years were provided by CAP (CAP, 2021). RCH for 2018 to 2019 were handled on a source-by-source basis with either a constant rate, data provided by CAP (CAP, 2021) or a constant median historic rate. Details on this by source of recharge are included in the *Simulated Inflows* section of this technical memorandum. Evapotranspiration and some groundwater underflow processes are implemented in the TAMA Model with the MODFLOW Evapotranspiration package (EVT) and MODFLOW Time-Varying Specified-Head package (CHD), respectively. Extended periods for these packages were not available. The most recent model input values for these packages (2010) were held constant over the interim period (2010-2020).

It should also be noted that the TAMA Model domain is not coincident with the TAMA boundary. The groundwater model encompasses small portions of the Santa Cruz AMA (SCAMA) to the south and the Pinal AMA (PAMA) to the northwest (Figure 3). To avoid confusion, many of the TAMA Model outputs were constrained to include only those model cells located within the TAMA boundary—thereby excluding those in the PAMA or SCAMA.

Table 2. TAMA groundwater model general parameters and characteristics (Mason & Hipke, 2013)

Model Component	Description	Values/Units
Simulation: Combined Steady-State-Transient	Years: 1940-2010; Steady-State: 1940: Transient: 1941-2010	Time = days Length = feet
Model Grid	130 Rows x 100 Columns; 3,200 mile^2	Model Cells = 0.5 mile^2 DELR = DELC = 2640 feet
Model Origin (Lower Left)	UTM, Zone 12, HARN 1983, feet	X = 1488661.47638 Y = 11494611.8537
Model Cell Types	No Flow, Constant Head, Variable Head, Specified Flux	
Boundary Conditions	Constant Head and Specified Flux	
UPW Package	Allows resaturation of cells that go dry	LAYWET = 0
Layer 1 – 3,105 active cells	Layer Type 1 – Unconfined Aquifer	Horizontal K; Min = 0.5 feet/day, Max = 250, Average = 35.3
Layer 2 – 4,524 active cells	Layer Type 3 – Confined / Unconfined Aquifer	Horizontal K; Min = 0.5 feet/day, Max = 110, Average = 16.5
Layer 3 – 4,954 active cells	Layer Type 3 – Confined / Unconfined Aquifer	Horizontal K; Min = 0.1 feet/day, Max = 55, Average = 3.8
Vertical Conductivity	Assigned as a ratio between horizontal K and vertical K values	Layer 1 = 10:1 Layer 2 = 10:1 to 20:1 Layer 3 = 15:1 to 30:1
Specific Yield	Volume of water yielded per unit area per unit change of water level in unconfined aquifer	Layer 1 = 0.08% to 20% Layer 2 = 0.05% to 0.18% Layer 3 = 0.05% to 0.12%
Specific Storage	Volume of water yielded per area per unit change in a confined aquifer's potentiometric surface	Layer 1 = N/A (Unsaturated) Layer 2 = 1.0×10^{-6} Layer 3 = 1.0×10^{-6}
Pumping	Assigned to all simulated well locations	feet^3 / day
Recharge	Applied to uppermost active cells	feet / day
Evapotranspiration	Assigned rates per cell; Extinction Depth 30 feet	feet / day
Numerical Solver	Generalized-Minimum-Residual (GMRES)	Head Closure Criteria: 0.01 feet Budget Error 864 feet^3/day

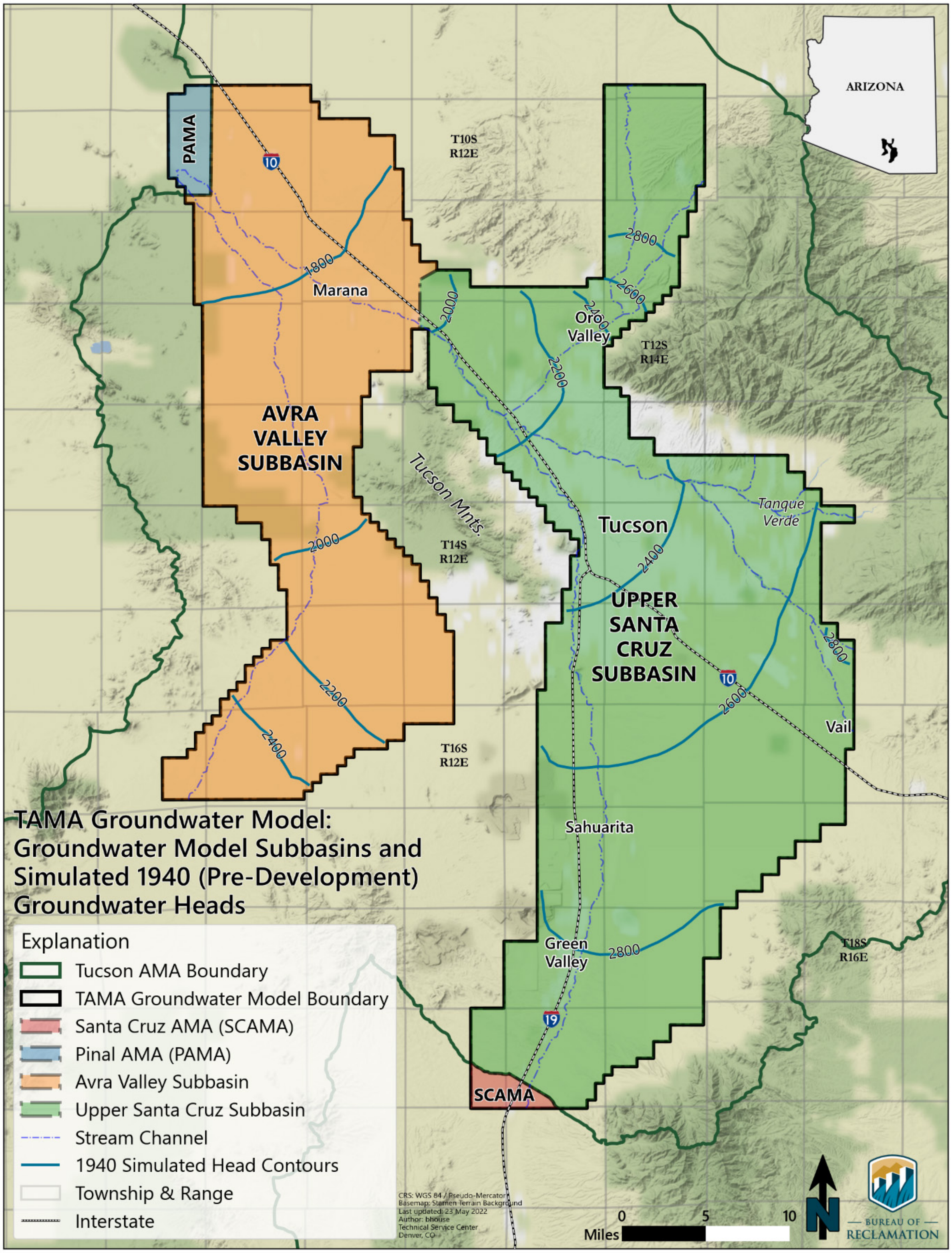

Figure 3. TAMA groundwater model subbasins and portions located outside the TAMA boundary. Contours of simulated groundwater head from 1940 (pre-development) in feet of elevation.

2. Groundwater Model Updates

The ADWR TAMA Model was updated for application to the Study. The active model domain was expanded in layers 1 and 2. The domain expansion allowed for wetting of model cells that were dry over the historical period (1940-2010). Section 2.1 provides details on this change. TAMA Model groundwater stresses were updated to fill the interim period (2010-2019 or 2018-2019) and incorporate projections of future stresses (2020-2060). Section 2.2 provides detail on updates to inflows (recharge) to the model while Section 2.3 provides detail on updates to outflows.

2.1. Active Model Domain

The TAMA Model active domain and hydrogeologic properties were developed by Mason & Hipke (2013). Personal communication with Dale Mason of ADWR indicated that the active domain for layers 1 and 2 was curtailed during model development where model cells in these layers were dry for the duration of the historical period (ADWR, 2018b). Model cells in these areas were set inactive to improve computational performance, not because aquifer material does not exist.

According to Mason (2018b), the active domains of layers 1 and 2 should be coincident with layer 3. These inactive cells in layers 1 and 2 should be activated if there were potential for wetting of historically dry cells. For example, the Avra Valley has experienced a significant change from its natural state with the construction of two major artificial recharge facilities (CAVSARP and SAVSARP). Though much of this change occurred during the period modeled by Mason & Hipke (2013), there remains potential for future wetting of historically dry cells as artificial recharge persists in the area and the resulting groundwater mounds continue to propagate outward from the facilities. Therefore, it was necessary to expand the active domain of layers 1 and 2 for this Study.

Hydrogeologic properties (i.e., hydraulic conductivity and storage parameters) were not assigned to these potentially active cells in the original TAMA Model input files from Mason & Hipke (2013). Groundwater modeling work commissioned by CAP (Montgomery and Associates, 2020) addressed this issue previously by activating cells in layers 1 and 2 to match the extent of layer 3. This work also assigned hydrogeologic properties to these activated cells. The MODFLOW input files containing these changes (BAS, DIS, and UPW) were provided by CAP for implementation in this Study (Montgomery and Associates, 2020). The updated active model boundaries and horizonal K values for model layers 1 and 2 are presented in Figures 4 and 5, respectively. The area between the original (blue) and updated (black) layer boundaries in Figures 4 and 5 are where the active domain was expanded. Hydrogeologic properties for model layer 3 were not changed from Mason & Hipke (2013).

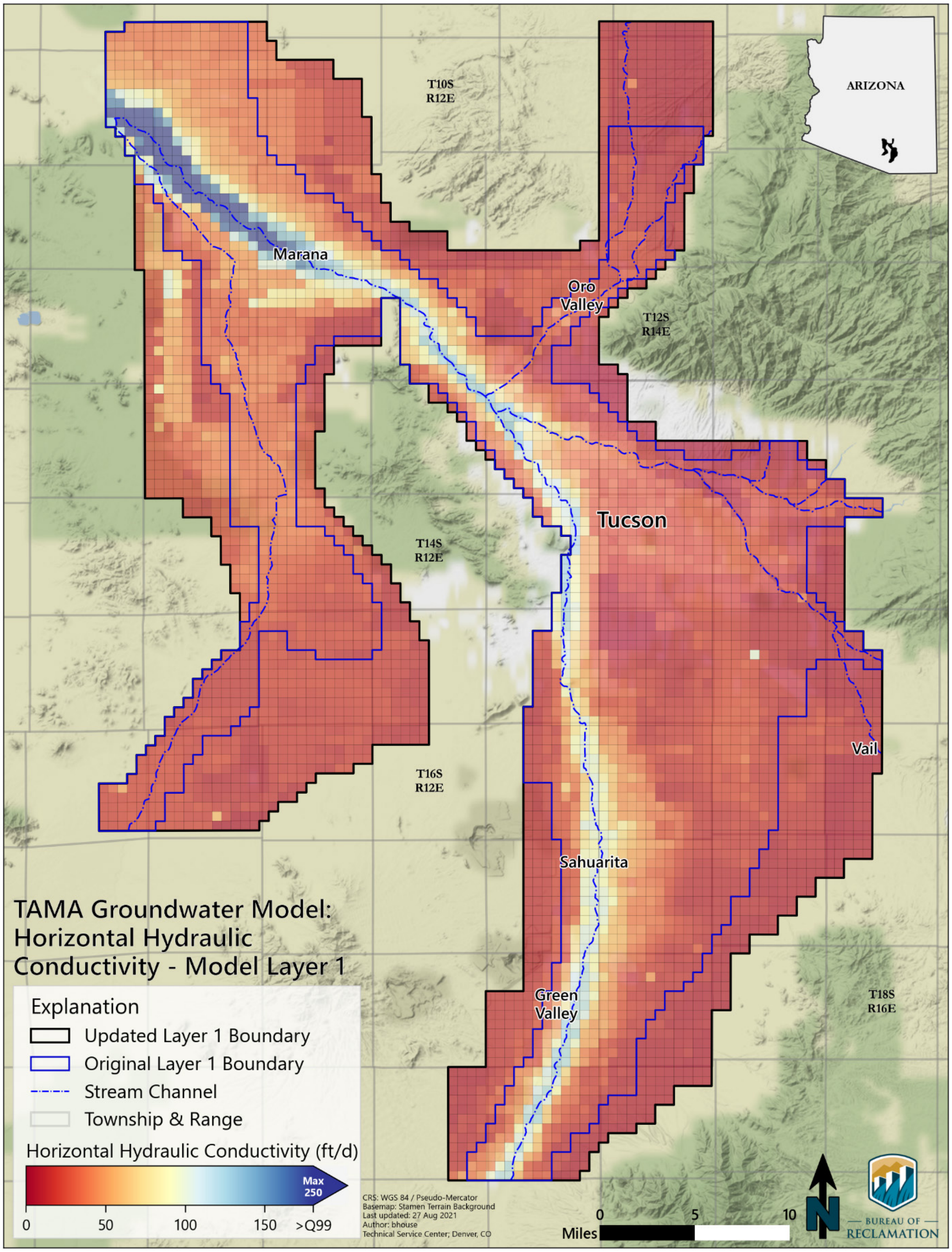

Figure 4. Updated horizontal hydraulic conductivity distribution for the TAMA Model layer 1. To provide detail in the expanded domain areas, the maximum value on the color bar was set to the 99th quantile. The area between the blue and black boundaries indicates where the active domain was expanded.

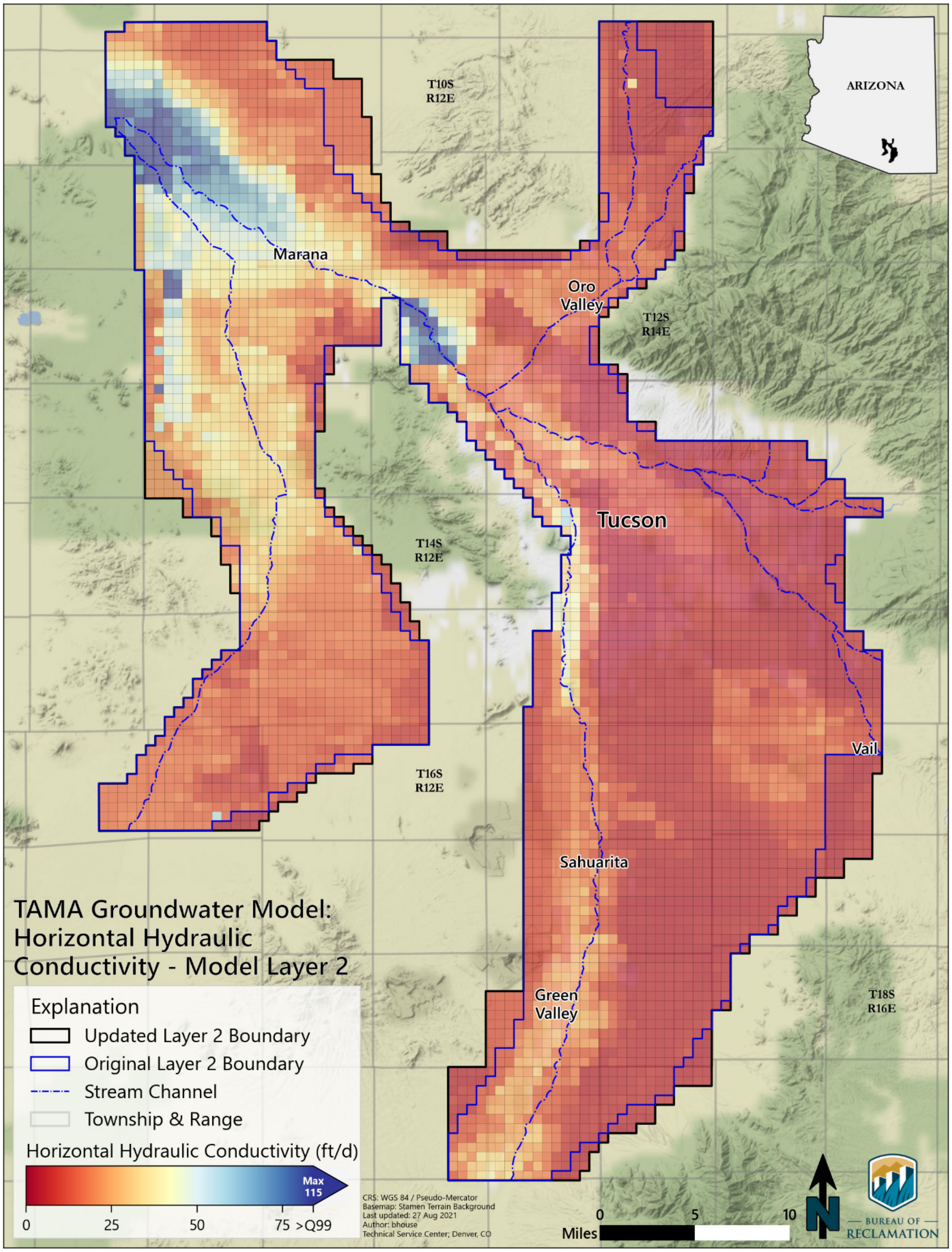

Figure 5. Updated horizontal hydraulic conductivity distribution for the TAMA Model layer 2. To provide detail in the expanded domain areas, the maximum value on the color bar was set to the 99th quantile. The area between the blue and black boundaries indicates where the active domain was expanded.

2.2. Simulated Inflows

Simulated inflows to the groundwater model (in order of descending magnitude) occur from: artificial recharge of CAP water and reclaimed water; infiltration of natural and reclaimed water-derived streamflow; mountain front recharge; underflow from adjacent basins; agricultural deep percolation; and seepage from mine tailings ponds. Each will be discussed below.

2.2.1. Artificial Recharge

Just under half of the total recharge within the Study Area over the projection period occurs at constructed artificial recharge facilities—legally designated as underground storage facilities (USFs). ADWR differentiates USFs as either “constructed” or “managed” (ADWR, 2022). Constructed facilities recharge water via percolation basins, etc. Managed facilities recharge water through discharge to a natural channel. Supplies for recharge include reclaimed water from water reclamation facilities (WRF; a.k.a. wastewater treatment plants) or Colorado River water imported via the CAP. Projections of recharge for these facilities within the Study Area were provided by CAP for 2018-2060 (CAP, 2021). This section of the Technical Memorandum covers the area’s constructed facilities, as well as the small managed Santa Cruz Heritage Recharge Project. Managed recharge projects for reclaimed water discharges from the region’s two metropolitan WRFs into the Santa Cruz River is covered in Section 2.2.3.

An extended RCH input file was provided by ADWR though 2017, which includes historical annual recharge rates from these facilities (ADWR, 2020a). Projections vary based on the Study climate and demand growth scenarios and include varying degrees of shortages of CAP water across the tiers identified in the *2019 Lower Basin Drought Contingency Plan*[3] (CAP, 2021). Projections were provided for the 17 permitted recharge facilities within the TAMA Model domain, listed in Table 3, for each S-D scenario. The locations of the recharge facilities listed in Table 3 are shown in Figure 7.

[3] https://www.usbr.gov/dcp/finaldocs.html

Table 3. Permitted recharge facilities within the project area.

USF Permit Number	Facility Name	Type
71-211276	SOUTHERN AVRA VALLEY STORAGE AND RECOVERY (SAVSARP) USF	Constructed
71-211284	PCRWRD CORONA DE TUCSON RECHARGE FACILITY USF	Constructed
71-221721	SADDLEBROOKE WATER RECLAMATION PLANT CONSTRUCTED USF	Constructed
71-222410	PROJECT RENEWS CONSTRUCTED UNDERGROUND STORAGE FACILITY	Constructed
71-224073	BLACK WASH USF – PIMA COUNTY RWRD	Constructed
71-224578	MARANA WRF RECHARGE PROJECT USF	Constructed
71-225060	TUCSON WATER SHARP USF	Constructed
71-228412	SANTA CRUZ RIVER HERITAGE PROJECT MANAGED USF	Managed
71-231174	GREEN VALLEY RECHARGE PROJECT USF	Constructed
71-520083	SWEETWATER RECHARGE FACILITIES USF	Constructed
71-561366	LOWER SANTA CRUZ REPLENISHMENT PROJECT USF	Constructed
71-563876	MARANA HIGH PLAINS EFFLUENT RECHARGE PROJECT USF	Constructed
71-564896	AVRA VALLEY RECHARGE PROJECT (FULL SCALE) USF	Constructed
71-577501	PIMA MINE ROAD FULL SCALE USF	Constructed
71-578806	CAVSARP FULL SCALE USF	Constructed
71-581379	ROBSON RANCH QUAIL CREEK, LLC USF	Constructed
71-595209	TOWN OF SAHUARITA	Constructed

Mason & Hipke (2013) found that temporal lagging of recharge at facilities to account for travel time through the vadose zone improved model calibration. Lagging over a three-year period with 30% the first year, 40% the second, and 30% the third year was found to yield reasonable results (Mason & Hipke, 2013). Figure 6 shows the historical and projected total annual lagged recharge by S-D scenario. Projected recharge was distributed spatially over groundwater model cells using the footprint of each recharge facility provided by ADWR. Where a recharge facility's footprint overlapped with multiple model cells, the proportion of the footprint overlap with a given cell was used to distribute the total recharge volume. Figure 7 presents a map of average recharge rates from artificial recharge facilities over the projection period and S-D scenarios. Recharge from facilities was implemented in the TAMA Model using RCH.

Most recharge from artificial recharge facilities occurs in the Avra Valley subbasin at the SAVSARP, CAVSARP, AVRP, and LSCRP facilities (Figure 7). The Pima Mine Road facility north of Sahuarita is projected to recharge the majority of water in the Upper Santa Cruz subbasin. For all S-D scenarios, recharge at facilities is projected to decline over the projection period due to reductions in available CAP supplies (Figure 6).

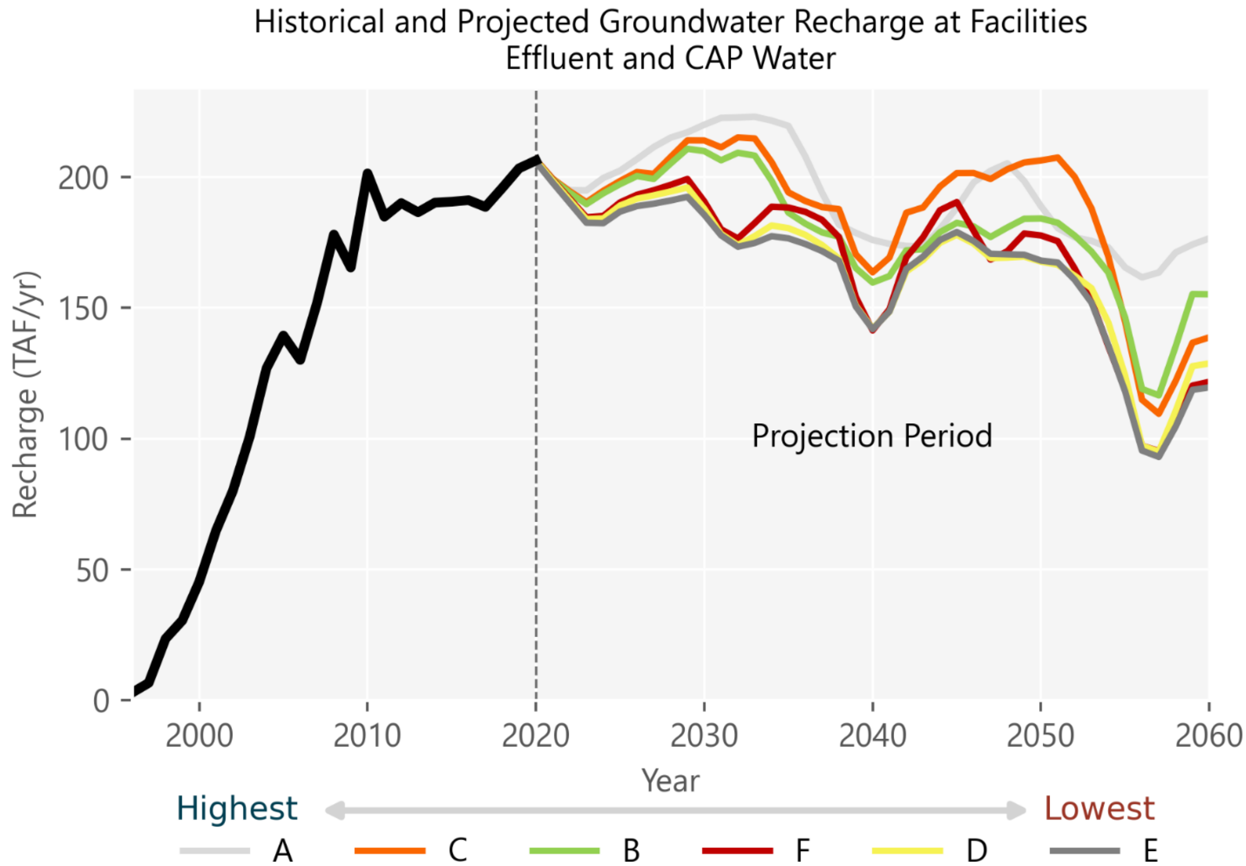

Figure 6. Historical and projected annual groundwater recharge at recharge facilities within the TAMA groundwater model boundary. Values are temporally lagged over a three-year period.

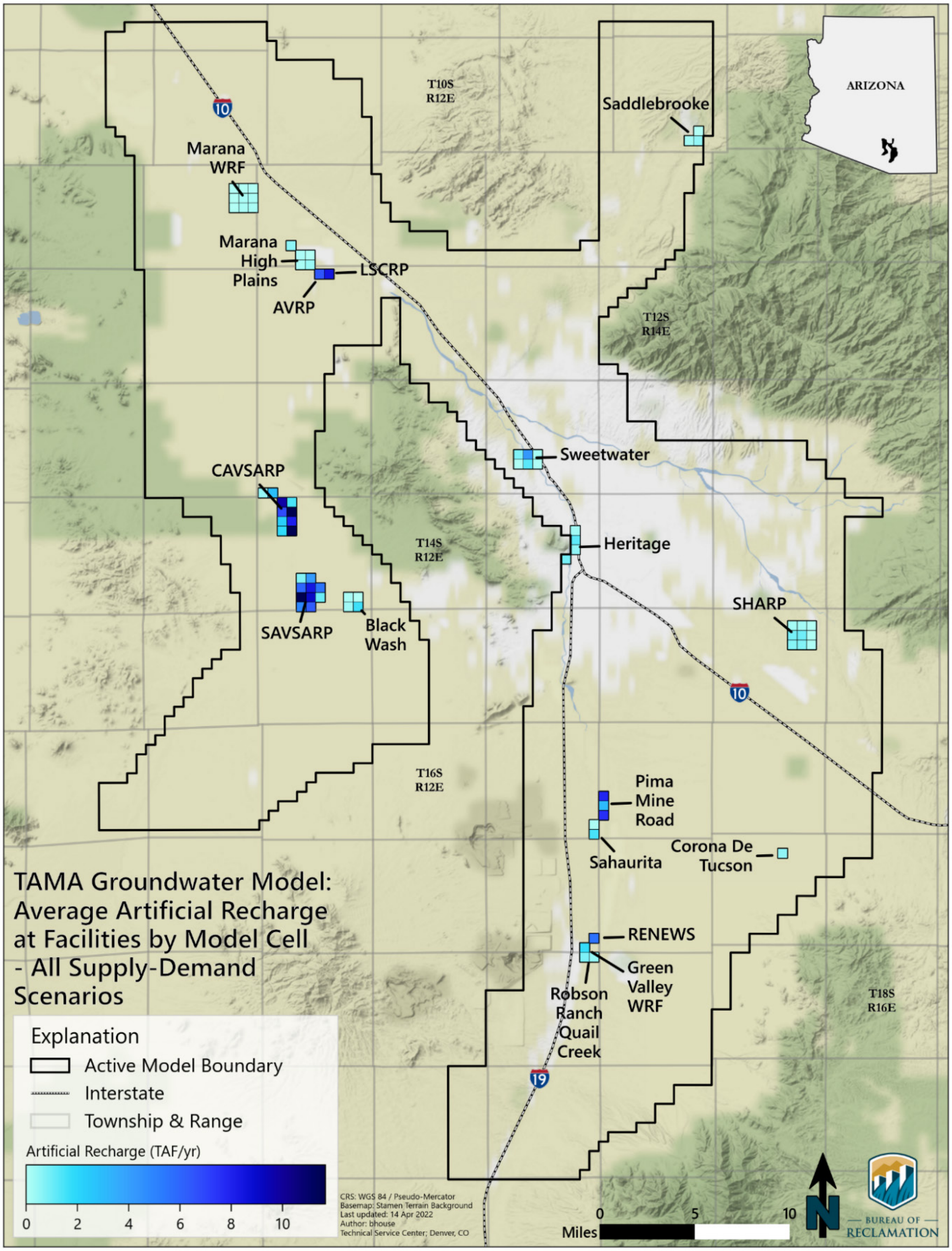

Figure 7. Map of average groundwater recharge from facilities over the projection period (2020-2060) and all S-D scenarios. Note that this map does not include the Santa Cruz Managed USF and the Lower Santa Cruz River Managed USF that receive reclaimed water from the Agua Nueva and Tres Rios WRFs. These managed recharge facilities are depicted in Figure 15.

2.2.2. Streamflow Infiltration

Infiltration of streamflow along natural channels constitutes a significant source of groundwater recharge within the TAMA. Mason & Hipke (2013) estimated that under pre-development conditions, streamflow infiltration accounted for 37% of recharge within the TAMA Model domain. Streamflow infiltration can vary greatly from year-to-year. Estimated annual streamflow infiltration during the historical period (1940-2010) ranges from a minimum of 15 TAF to a maximum of 450 TAF (Mason and Hipke, 2013).

Mason & Hipke (2013) calculated initial estimates of groundwater recharge from streamflow infiltration using a method developed by Burkham (1970). This method uses a power-law relationship between mean monthly streamflow discharge at a given gage (in cubic feet per second [cfs]) and mean monthly infiltration (cfs):

$$Infiltration\ Rate = C \times Mean\ Monthly\ Discharge^{0.8} \quad \text{Equation 1}$$

where C is a reach-specific fitting parameter.

Burkham (1970) assigned C parameters for the major streams and washes within the Study area based on analysis of measured discharge data from flow events (Figure 8). Given the length of a reach, the $C_{per\ mile}$ (1/mile) was calculated for several reaches by Burkham (1970). Those reaches for which Burkham (1970) did not calculate the $C_{per\ mile}$ were calculated as part of this Study. The Burkham (1970) reaches and $C_{per\ mile}$ parameters are presented in Figure 8.

Current Climate Scenario

Streamflow infiltration is implemented in the TAMA Model with RCH. An RCH input file with an extended period (1940-2017) was provided by ADWR (2020a). An interim period of 2018 to 2019 remains before the start of the projection period in 2020. Inflows from all sources (except underflow) are combined in the RCH for a given year and cell. This complicates parsing inflows by source. An RCH with streamflow infiltration removed was provided by ADWR for 1940 to 2010 (ADWR, 2018a). The difference between this and the RCH from Mason & Hipke (2013) provided an approximation of historic streamflow infiltration by model cell. The median streamflow infiltration between 2000 and 2010 was applied for the years 2018 and 2019. This results in approximately 71.7 TAF/yr of streamflow infiltration recharge for these years.

As the Study progressed, a dataset of streamflow infiltration rate by year and model cell became available from ADWR with a period of 1940 to 2015 (ADWR, 2020b). The period 1999 to 2013 is identified in the TAMA Fourth Management Plan as, "…generally representative of 'normal' (streamflow) conditions" (ADWR, 2016). There is a 2% difference in the median total streamflow infiltration over this period and the result above; therefore, streamflow infiltration for 2018 and 2019 were not changed when this new dataset became available.

Streamflow infiltration rates for the current climate scenario reflect the period 1999 to 2013. As stated above, these years are "generally representative of 'normal' (streamflow) conditions" (ADWR, 2016). Data for these years were extracted from the streamflow infiltration rate dataset by year and model cell discussed above (ADWR, 2020b). Streamflow infiltration rates for the projection period (2020-2060) were defined by repeating rates for the period 1999-2013 in sequence.

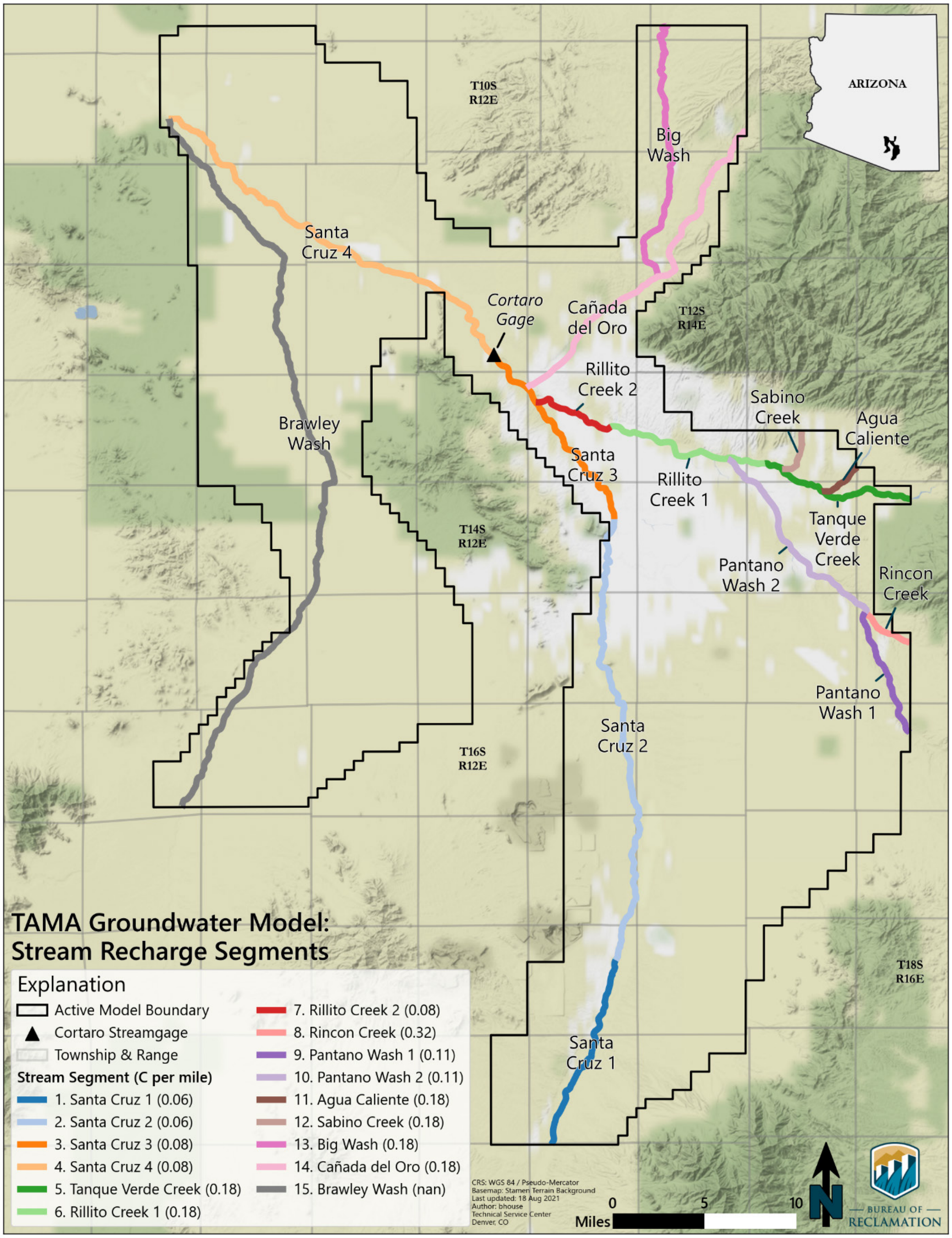

Figure 8. Study area stream recharge segments. Where available, Burkham (1970) $C_{per\ mile}$ values are included in the legend. General flow directions are south to north and out the northwest corner of the model domain. Location of the Cortaro Gage noted. Brawley Wash was not evaluated in Burkham (1970).

Best-case and Worse-case Climate Scenarios

Streamflow infiltration for the best-case and worse-case future climates was developed from projections of mean monthly streamflow. Infiltration to the groundwater was computed using the projected mean monthly streamflow and Equation 1. Projected changes in streamflow were developed based on a combination of future climate projections from GCMs, a stochastic weather generator, and rainfall-runoff modeling (Reclamation, 2021).

Downscaled climate projections were first used to inform a stochastic weather generator based on projected changes in precipitation and temperature under the best-case (RCP 4.5) and worse-case (RCP 8.5) climates (see Table 1). A stochastic weather generator was then used to generate a suite of one hundred realizations of daily precipitation and temperature under each climate scenario. Realizations of precipitation and temperature were used as input to the Sacramento Soil Moisture Accounting (Sac-SMA) rainfall-runoff model to generate corresponding realizations of daily streamflow (Reclamation, 2021). In addition to realizations of the best-case and worse-case climates, a historical case was also developed by forcing the Sac-SMA model with observed historical precipitation and temperature.

Reclamation (2021) grouped the climate analysis into 30-year periods. These included 2020-2049, referend to as the "near future", and 2050-2079, referred to as the "far future". To align with the projection period (2020-2060) of this analysis, the complete near future period (2020-2049) and the initial third of the far future period (2050-2060) were used. More information on the downscaled climate projections and development of weather and streamflow realizations are detailed in the *Lower Santa Cruz River Basin Study Hydroclimate Analysis* Technical Memorandum ENV-2020-056 (Reclamation, 2021).

Sac-SMA discretizes the Study area into subbasins and simulates streamflow discharge at each subbasin outlet. Subbasin outlets align with existing streamflow gage stations (Figure 9; Table 4). USGS streamgage locations are used in most cases. The Pima County Regional Flood Control District (PCRFCD) also maintains a series of streamgages throughout the Study area known as the ALERT System. The Sac-SMA gages are aligned with ALERT System gages in several locations where USGS gages are not present.

Table 4. Summary of Sac-SMA streamflow projection locations

Sac-SMA Gage Id	Gage Name	USGS Gage Id	Burkham (1970) Reach Name	$C_{per\ mile}$
STB	Santa Cruz River at Tubac, AZ	09481740	Santa Cruz 1	0.06
SCC	Santa Cruz River at Continental, AZ	09482000	Santa Cruz 2	0.06
SBC	Sabino Creek near Tucson	09484000	Sabino Creek	0.18
ACH	Agua Caliente Wash near La Milagrosa	2253*	Agua Caliente Wash	0.18
TQR	Tanque Verde Creek near Tucson, AZ	09483100	Tanque Verde Creek	0.18
RIN	Rincon Creek near Tucson	09485000	Rincon Creek	0.32
PNT	Pantano Wash near Vail	09484600	Pantano Wash 1	0.11
PWB	Pantano Wash at Broadway Blvd.	09485450	Pantano Wash 2	0.11
TVC	Tanque Verde at Tucson, AZ	09484500	Rillito Creek 1	0.18
RIL	Rillito Creek Tucson at Dodge Blvd.	09485700	Rillito Creek 1	0.18
BWC	Big Wash Canada Del Oro	1174*	Big Wash	0.18
CDO	Canada Del Oro below Ina Rd, near Tucson	09486350	Canada Del Oro	0.18
GRB	Canada Del Oro Golder Road Bridge	1103*	Canada Del Oro	0.18
RIC	Rillito Creek at La Cholla Blvd	09486055	Rillito Creek 2	0.08
CSC	Santa Cruz River at Cortaro	09486500	Santa Cruz 4	0.08
TSC	Santa Cruz River at Tucson	09482500	Santa Cruz 3	0.08
SCT	Santa Cruz River at Trico Rd, near Marana	09486520	Santa Cruz 4	0.08

*PCRFCD ALERT system streamgage number

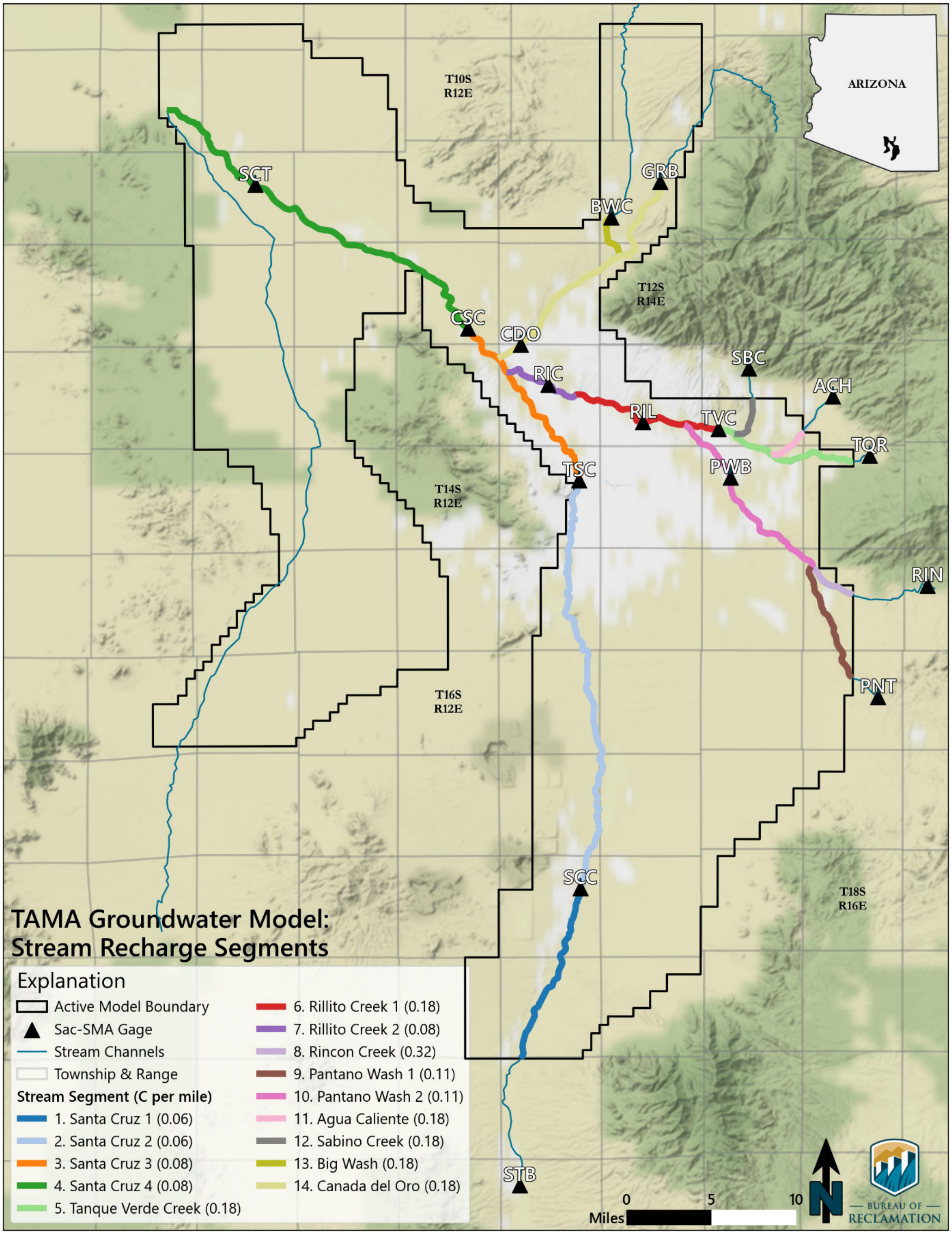

Figure 9. Sac-SMA subbasin outlet locations along stream channels within the project area. Sac-SMA subbasins are assigned a three-letter ID. This ID is located above each outlet location (black triangle) on the map.

The downscaled climate projections used to force the Sac-SMA model in Reclamation (2021) were not bias-corrected; instead, streamflow projections were bias-corrected to the observed streamflow record. The purpose of bias-correction is to correct for systematic biases in the model simulations—in this case, both in the GCMs and Sac-SMA. For this Study, bias-correction is based on the relationships between simulated streamflows from the Sac-SMA model when forced with historical or future climate conditions and the observed streamflow record. The approach uses the cumulative probability distribution function (CDF) of mean monthly streamflow (by month) from the observed record (blue line in Figure 10), Sac-SMA historical simulation (green dashed line in Figure 10), and Sac-SMA projection simulation (red dashed line in Figure 10) to produce a transformed version of the observed record (black line in Figure 10).

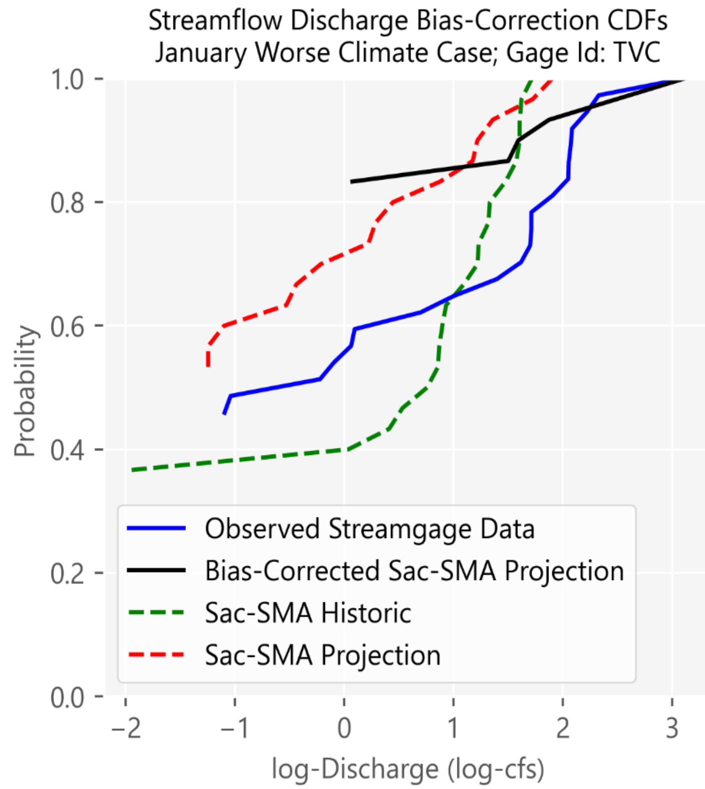

Figure 10. Illustrative CDFs for streamflow bias-correction process. Data are from January of the worse-case climate for Sac-SMA gage TVC.

The relationship between the simulated historical CDF and simulated projected CDF (the difference between the green and red dashed lines in Figure 10) is imposed on the observed record through quantile (exceedance probability) mapping. This preserves the range of observed streamflow magnitudes but transforms the probability of a particular flow occurring. This transformation represents the simulated change in streamflows between the historic and projected conditions. The sequencing of flows from the Sac-SMA projections is preserved through the projection period. The result is a magnitude bias-corrected monthly mean streamflow with temporal sequencing from the Sac-SMA projections (black line in Figure 10). Additional details on the streamflow bias-correction method are discussed further in Appendix A of this technical memorandum.

Comparison of the historic simulated streamflow infiltration (ADWR, 2020b) and the projected streamflow infiltration under the best-case climate (Figure 11) and worse-case climate (Figure 12) indicate reasonable temporal sequencing and magnitude over the projection period. The best-case climate includes greater streamflow infiltration than the worse-case climate. The final 10-years (2050-2060 of the "far future") of the projection period includes greater streamflow infiltration compared to the initial 30-years (2020-2049 or "near future") for both climate scenarios. These characteristics are in-line with the results of Reclamation (2021). Note: The projected time series of streamflow infiltration in Figures 11 and 12 represent a single plausible future out of the many plausible futures generated in Reclamation (2021). These results do not represent a prediction of streamflow infiltration for a given future year.

Where streamflow observation data had a short period of record, calculated recharge for the projection period was sometimes found to deviate significantly from what had been applied in Mason & Hipke (2013). In these cases, gaps in the observed record were filled based on a monthly disaggregation of the annual recharge from streamflow infiltration applied in Mason & Hipke (2013). These values were then added to the observed data during bias-correction.

A potential limitation of this bias-correction method is that the maximum observed mean monthly streamflow cannot be exceeded during the projection period. As a result, a projected increase in mean monthly streamflow could be muted. The potential impact of this limitation is reduced given that streamflow is aggregated to monthly mean. Also, many of the streamgages in the Study area were active during the high precipitation events in 1983 and 1993 which resulted in catastrophic flooding and significant groundwater recharge (Roeske, et al. 1985; House 1993; Mason & Hipke, 2013 RCH file). The method also assumes that the biases present in the historical simulation period are representative of biases in the projected simulation period.

An alternative method of bias-correction that repeats the historic sequencing of flow events is possible. This would entail perturbing the observed streamflow record based on the difference between the historical and projected simulated streamflow. For application to this Study, a reconstruction of the "observed" streamflow record would be necessary, as many streamgages in the Study area have gaps in the period of record. Some methodological uncertainty in the projections of streamflow infiltration is present in these results due to the selection of the quantile-mapping method described above for bias-correction. This uncertainty could be constrained by evaluating the impact on the results based on which method is applied.

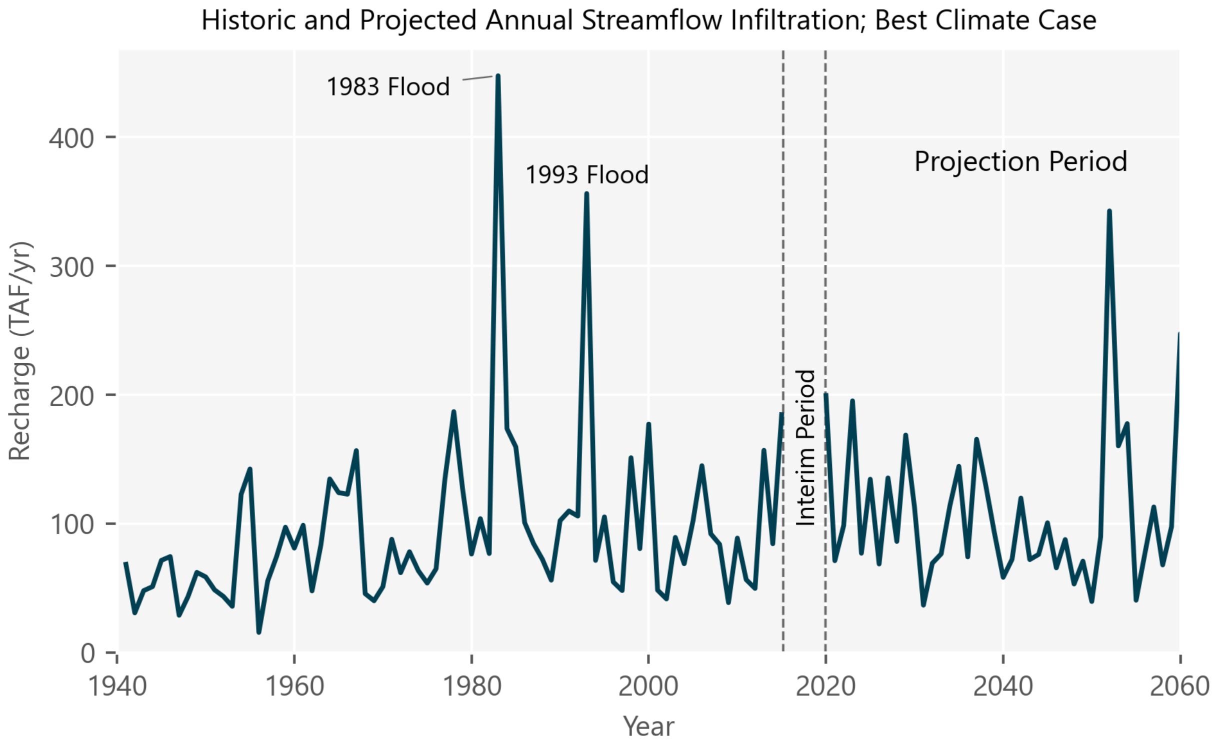

Figure 11. Historic and best-case climate projected annual streamflow infiltration simulated in the TAMA Model.

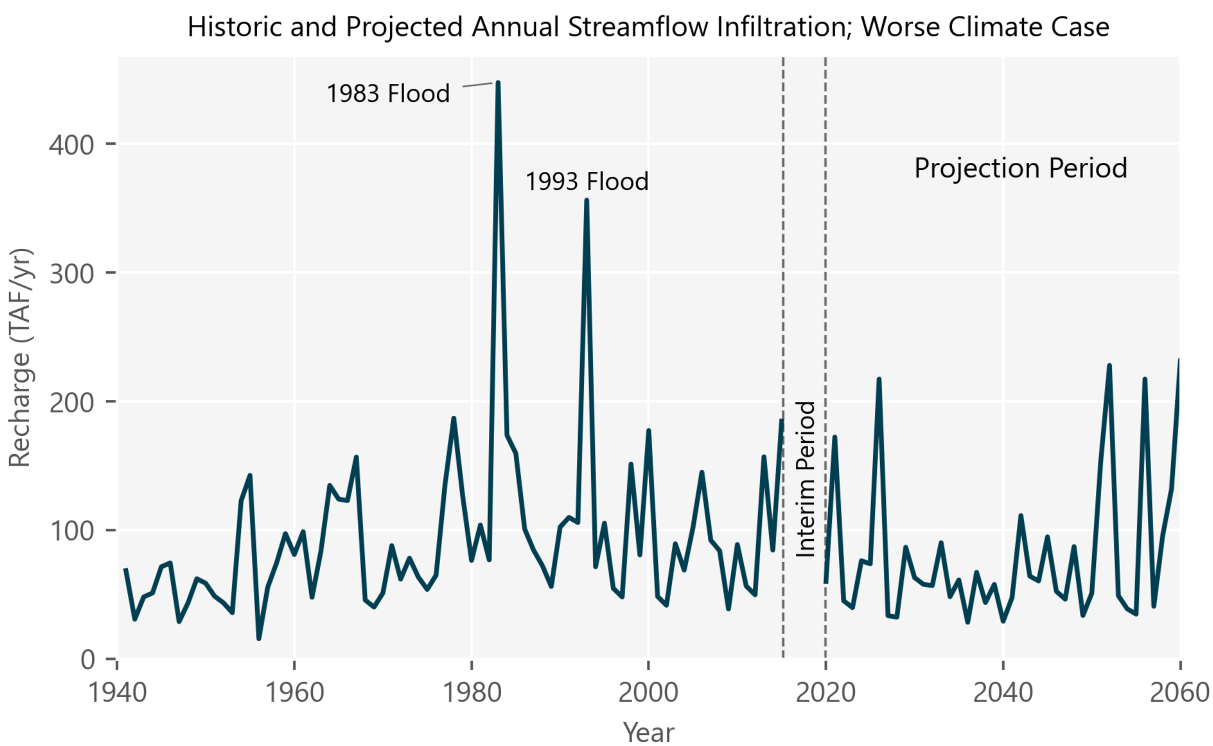

Figure 12. Historic and worse-case climate projected annual streamflow infiltration simulated in the TAMA Model.

The Tres Rios and Agua Nueva water reclamation facilities (WRFs), which are located within the Tucson metropolitan area, discharge reclaimed water to the reach of Santa Cruz River near Tucson (SCR; "Santa Cruz 3" in Figure 8). Above the Cortaro streamgage (Sac-SMA ID: CSC; USGS ID: 09486500; Figure 8), Mason & Hipke (2013) calculate recharge from this reclaimed water separately from natural streamflow. (Details on this processing are discussed below in the *Reclaimed Water Discharge to Santa Cruz River* section of this Technical Memorandum.) Below the Cortaro gage, no distinction is made between natural streamflow and reclaimed water. The Sac-SMA model accounts for this reclaimed water with a constant additional discharge of 53 cfs at the CSC/Cortaro gage (Figure 9). To account for expected future changes in reclaimed water discharged to the SCR, the CSC gage discharge was adjusted based on the reclaimed water remaining in the stream channel that had not infiltrated above the gage.

Equation 1 was applied to the transformed (bias-corrected) version of the projected mean monthly streamflow timeseries to produce estimates of future groundwater recharge from streamflow infiltration. Data from each Sac-SMA gage shown in Figure 10 was processed in turn—starting with the upstream gages and working downward. Recharge was distributed to cells underlying the stream segments by applying Equation 1 on a cell-by-cell basis and routing the remaining flow to the next downstream cell/reach. Where a confluence occurs mid-segment, the outflow of the tributary segment was added during the routing process. Multiple Sac-SMA gages are located outside the TAMA Model domain. In these cases, Equation 1 was applied to the portion of the segment outside the domain first and the remaining flow routed within the model.

Groundwater recharge from streamflow infiltration was processed for each of the 100 Sac-SMA realizations for both the best-case and worse-case climates. Though the groundwater model is capable of producing results for all realizations, a single realization was selected to align with the methodology applied by CAP for the data provided for the Study. The median of the 100 recharge realizations for each climate scenario was selected for use in the modeling analysis. Prior to applying the selected realizations in the TAMA Model, the realizations were inspected to ensure that they exhibited reasonable temporal sequencing compared to the historic period (Figures 11 and 12).

Note that Burkham (1970) did not address recharge along Brawley Wash in Avra Valley and Big Wash in Falcon Valley (locations in Figure 8). Mason & Hipke (2013) developed a time series of streamflow infiltration for Brawley Wash based on limited stream gage data and precipitation; however, documentation on the methodology is limited. For Big Wash, long-term average recharge rates from the previous iteration of the TAMA Model were adjusted based on precipitation data and observed groundwater heads during calibration (Mason & Hipke, 2013). Communication with Dale Mason at ADWR indicated that in future iterations of the model ADWR planned to forgo temporal variation in recharge along Brawley and Big Wash for a long-term mean constant rate as it did not have significant impact on simulated groundwater conditions (ADWR, 2018c).

For this Study, recharge along Brawley and Big Wash was assigned a constant rate through both the interim (2018-2019) and projection periods (2020-2060). Mason & Hipke (2013) developed a relationship between local precipitation data and streamflow to fill gaps in records at several streamgages in these areas. The recharge rates along Brawley and Big Wash were set to the simulated recharge assigned by Mason & Hipke (2013) for the year with median precipitation at the Cooperative Observation Network (COOP[4]) Anvil Ranch station (ID: USC00020287) over the period 1946-2010. Combined, recharge along Brawley and Big Wash accounts for 2.9 TAF/yr.

Streamflow infiltration was implemented in the TAMA Model using RCH. Maps of mean recharge rates by model cell along stream channels from both natural and reclaimed water sources for each climate scenario are shown in Figures 15 (best-case), 16 (current), and 17 (worse-case). Results from the *Reclaimed Water Discharge to Santa Cruz River* section of this Technical Memorandum contribute to the recharges rate shown in these figures.

2.2.3. Reclaimed Water Discharge to Santa Cruz River

Reclaimed water from WRFs is an important a source of recharge within the Study area. A portion of the reclaimed water within the basin is discharged to the Santa Cruz River (SCR), where it contributes to streamflow infiltration. Most of the remaining reclaimed water is routed to artificial recharge facilities. This section addresses recharge from reclaimed water discharged to the SCR; recharge from reclaimed water routed to artificial recharge facilities is addressed above in the *Artificial Recharge* section of this Technical Memorandum. Note that the managed Santa Cruz Heritage Recharge Project is also discussed in the *Artificial Recharge* section because it is a small, controlled project and is not associated with a WRF.

The Agua Nueva WRF (replacement for the former Roger Road WRF) and Tres Rios WRF (replacement for the former Ina Road WRF) both discharge reclaimed water to the SCR near Tucson (Figure 15). Recharge along the reach of the SCR between the WRFs' respective discharge points and the Cortaro gage ("Santa Cruz 3" in Figure 8) is calculated separately from streamflow infiltration from natural flows. Downstream of the Cortaro gage ("Santa Cruz 4" in Figure 8), recharge from infiltration of natural and reclaimed water flows are calculated jointly.

Mason & Hipke (2013) based initial estimates of recharge above the Cortaro gage on an infiltration study by Galyean (1996); however, details of how the analysis of Galyean (1996) was applied to the TAMA Model are unclear. Galyean (1996) estimated reclaimed water infiltration along the SCR with data collected from 1990 to 1993. At that time reclaimed water was discharged in the SCR from the Roger and Ina Road WRFs. Beginning in 2013, reclaimed water was discharged from the new Agua Nueva and Tres Rios WRFs. Reclaimed water discharge from the older Roger and Ina Road WRFs was of a lower quality and stimulated the development of a biological sealing layer (*schmutzdeche*) along the streambed. This layer reduced infiltration and groundwater recharge from the reclaimed water. With completion of the Agua Nueva and Tres Rios WRFs in 2013, and subsequent decommissioning of the Roger and Ina Road WRFs, the quality of reclaimed water discharged to the SCR increased and no longer stimulates *schmutzdeche* development. This has resulted in a state change in reclaimed water infiltration in the SCR since 2013; therefore, the results of Galyean (1996) are not applicable to the interim (2018-2019) and projection (2020-2060) periods evaluated in this Study.

Instead, recharge from reclaimed water discharged to the SCR from the Agua Nueva and Tres Rios WRFs was estimated using a method provided by the Study Partners that is used for recharge accounting purposes. This method estimates a percentage of the total daily reclaimed water discharge that infiltrates in the SCR above the Cortaro gage (USGS ID: 09486500) on days where no other measurable inflows to the reach occur. A period of record from 2008 to 2018 of

[4] https://climate.usu.edu/mapServer/mapGUI/index.php

daily WRF discharge data was available for this analysis. Days where flow was measured at either Santa Cruz at Tucson (09482500), Rillito at La Cholla (09486055), or Cañada Del Oro (09486350) were eliminated from the analysis. The percentage of reclaimed water infiltrated was then calculated as:

$$\%\,Infiltration = \left(1 - \frac{Daily\ WRF\ Discharge\ to\ SCR - Daily\ Discharge\ at\ Cortaro}{Daily\ WRF\ Discharge\ to\ SCR}\right) \times 100\%$$

According to this analysis, prior to the increase in reclaimed water quality (2008-2012), an estimated 19% of total daily WRF discharge to the SCR infiltrated above the Cortaro gage (n=2147). Following the increase in reclaimed water quality (2013-2018) an estimated 28% of total daily WRF discharge to the SCR infiltrated above the Cortaro gage (n=1828). These results support the assumed state change (increase) in reclaimed water recharge in the SCR when the older Roger and Ina Road WRFs were replaced by the Agua Nueva and Tres Rios WRFs.

The method used to spatially distribute recharge from natural streamflow infiltration over the TAMA Model cells was also applied to distribute recharge from infiltration of reclaimed water (Burkham, 1970; see the *Streamflow Infiltration* section above for more detail). The $C_{per\ mile}$ parameter was calibrated such that 28% of WRF discharged to the SCR infiltrates above the Cortaro gage, as estimated from the available data. The 2008-2018 mean daily WRF discharge to the SCR was used for the calibration. A $C_{per\ mile}$ of 0.288 was found to be satisfactory. Over the projection period of this Study, Equation 1 with a $C_{per\ mile}$ of 0.288 was used to calculate infiltration above the Cortaro gage from Agua Nueva and Tres Rios WRFs discharges to the SCR.

Projections of annual reclaimed water discharge to the SCR from the Agua Nueva and Tres Rios WRFs were provided by CAP (CAP, 2021). Projected annual reclaimed water discharge was disaggregated to monthly values for consistency with projected streamflows from Reclamation (2021). The percentage of annual total discharge in a given month was estimated from daily WRF discharge data (aggregated to monthly) for the period 2008-2018. For the analysis, data for Agua Nueva WRF were combined with data for Roger Road WRF, and data for Tres Rios WRF with data for Ina Road WRF. These monthly percentages were then used to disaggregate the annual total projections provided by CAP to monthly totals.

With the annual projections of WRF discharge to the SCR disaggregated to monthly values and the calibrated $C_{per\ mile}$ (0.288), groundwater recharge above the Cortaro gage was calculated by model cell over the projection period for all S-D scenarios (see Table 1). Recharge from WRF discharge to the SCR during the interim period is included with the streamflow infiltration, discussed above in the *Streamflow Infiltration* section of this Technical Memorandum. Infiltration of WRF discharge to the SCR was implemented in the TAMA Model using RCH. The resulting annual total recharge over the projection period by S-D scenario is presented in Figure 13. Figure 13 indicates that the scenarios tend to group based on demand growth case (e.g., scenarios F and C include rapid/outward demand growth). Note that recharge below the Cortaro gage is incorporated within the natural streamflow recharge calculation.

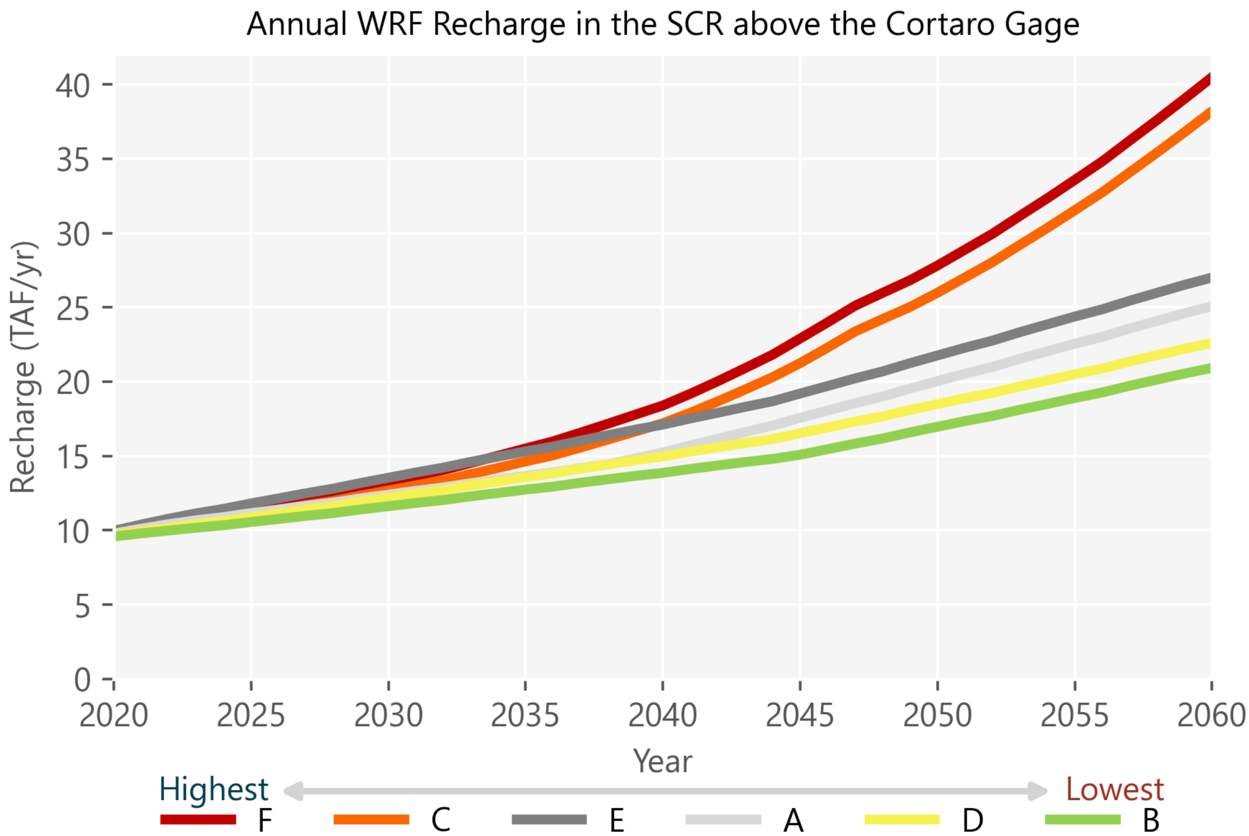

Figure 13. Projected annual groundwater recharge from WRF discharge to the SCR above the Cortaro gage. Note S-D scenarios tend to group based on demand/growth cases case due to similar population growth projections (e.g., F and C are rapid/outward demand growth scenarios).

Combining the recharge from reclaimed water discharge to the SCR above the Cortaro gage (described in this section) and the recharge from natural and reclaimed water streamflow occurring instream channels (described in the *Streamflow Infiltration* section above), yields estimates of total recharge occurring from infiltration along stream channels within the TAMA Model domain. The cumulative sum of annual infiltration along stream channels (from both natural and reclaimed water sources) by S-D scenario is shown in Figure 14. An apparent grouping by climate scenario highlights the impact of climate on recharge along stream channels. This is due to the impact of climate on natural streamflow, which in turn impacts streamflow infiltration, and not due to a significant relationship with demand growth as was seen in Figure 13.

The impact of demand growth on infiltration along stream channels can be seen by comparison of S-D scenarios with identical climate but different demand growth scenarios (e.g., scenario C [orange] vs. B [green]). The magnitude of this difference is markedly smaller than that related to different climate scenarios. The best-case climate is also shown to have more recharge overall than the current climate scenario. This is due to projected increases in natural streamflow above historical rates in some areas of the Sac-SMA model during the projection period (Reclamation, 2021).

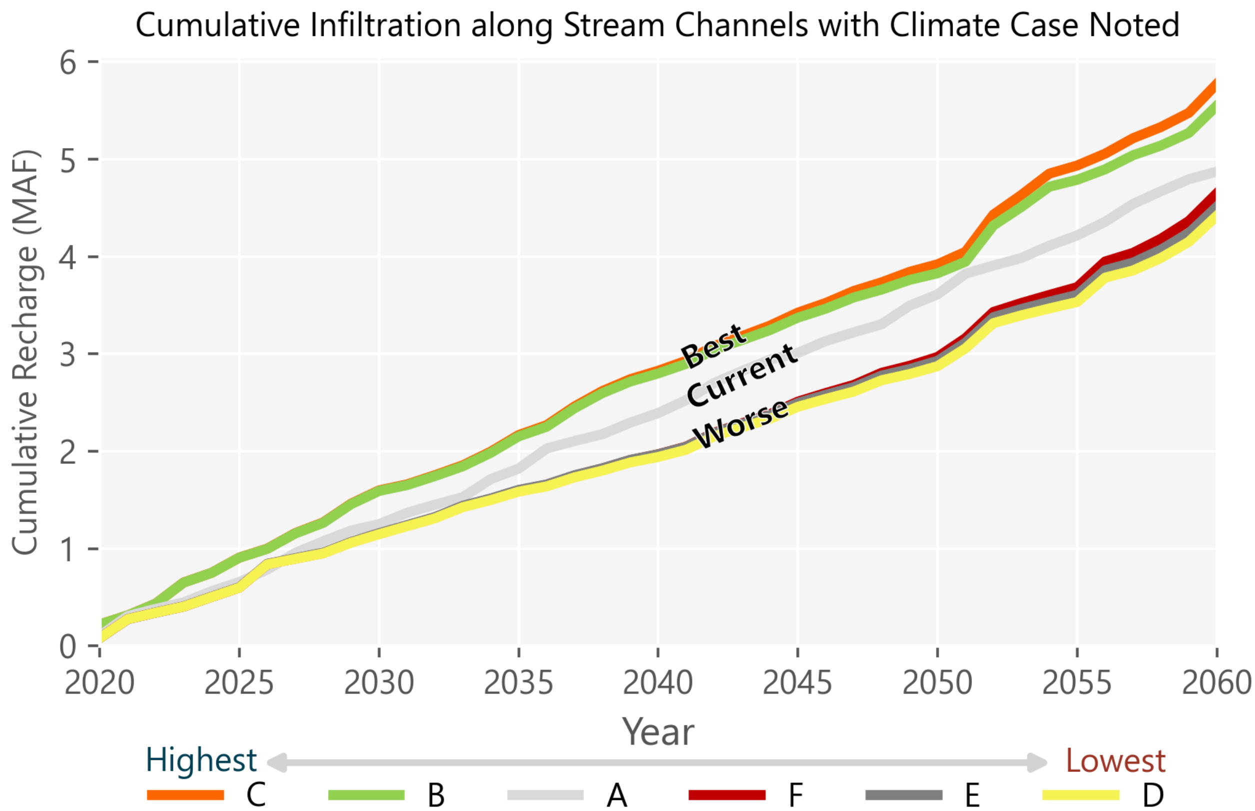

Figure 14. Cumulative sum of annual infiltration along stream channels from natural and reclaimed water sources. Study climate scenario is noted atop the related S-D scenarios.

Maps of average annual recharge rates by model cell along stream channels (from both natural and reclaimed water sources) for each climate scenario are shown in Figures 15 (best-case), 16 (current), and 17 (worse-case). The impact of reclaimed water discharge to the SCR is apparent in all climate scenarios in cells along the stream channel to the northwest of the WRF discharge locations. These figures indicate that most stream channel recharge occurs in the Tanque Verde area, Rillito Creek, and SCR northwest of Tucson.

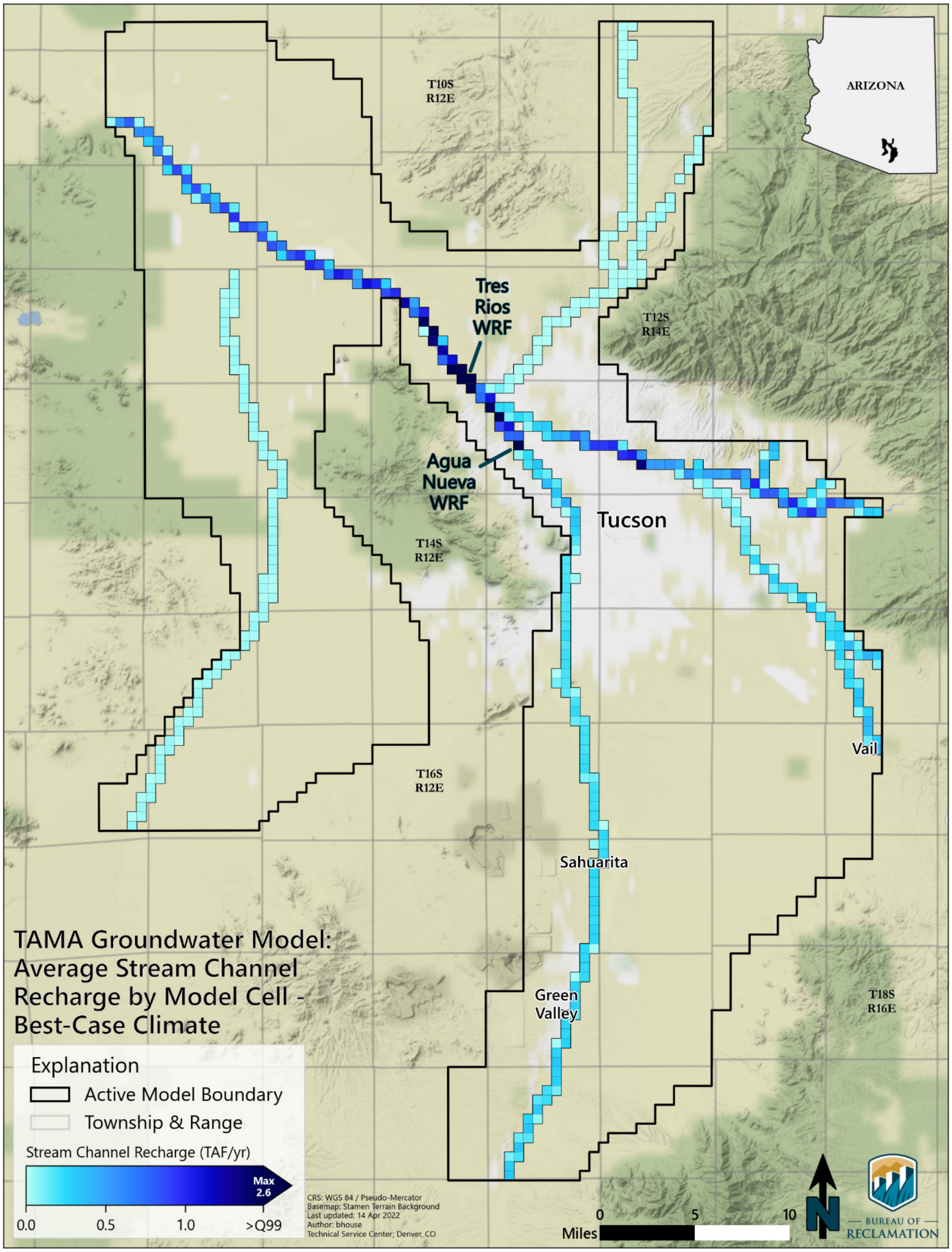

Figure 15. Average annual groundwater recharge from streamflow (both natural and reclaimed water) for the best-case climate S-D scenarios (B and C) over the projection period. For clarity, the maximum value on the color scale was set to the 99th quantile. Figures 15, 16, and 17 share a color scale.

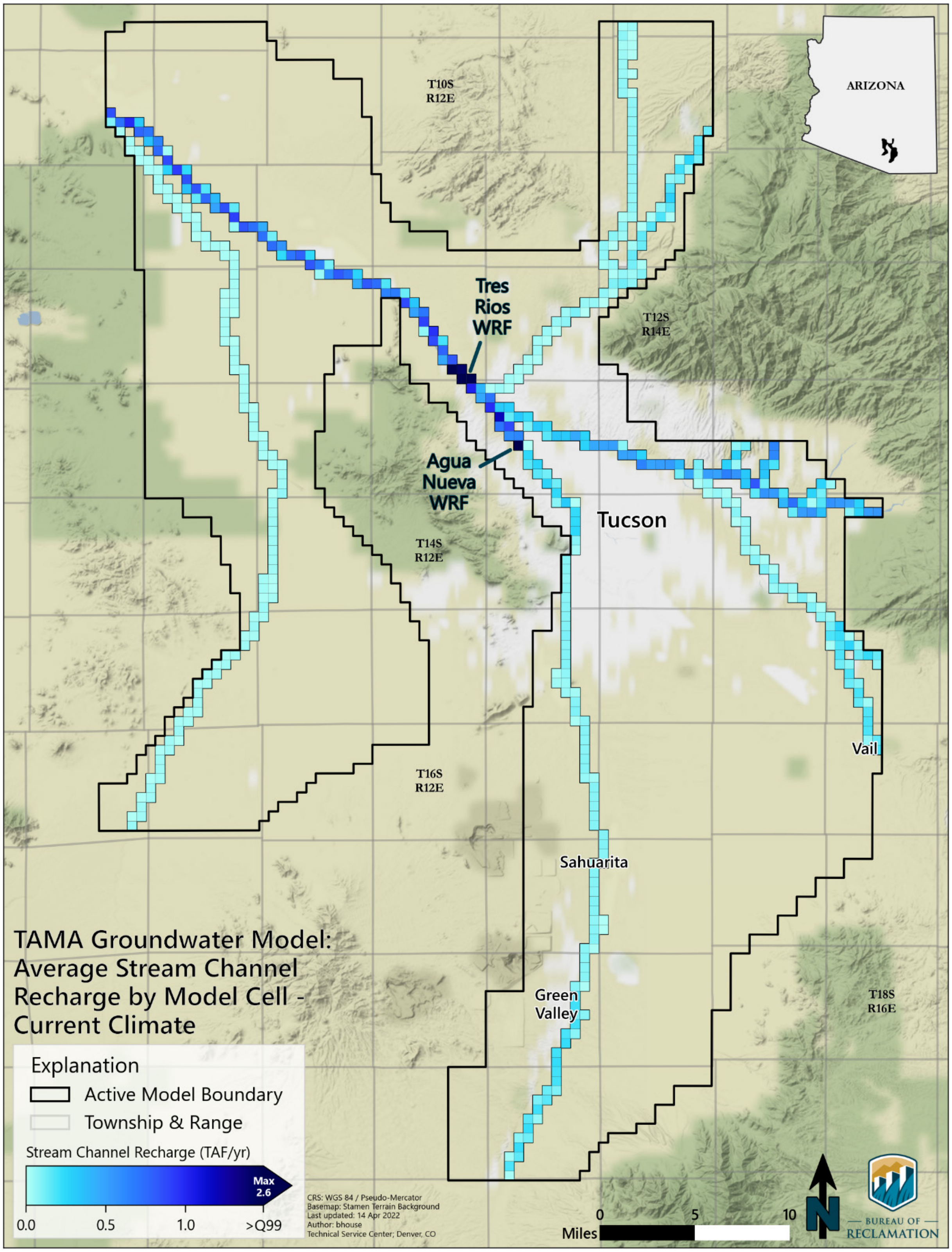

Figure 16. Average annual groundwater recharge from streamflow (both natural and reclaimed water) for the current climate S-D scenario (A) over the projection period. For clarity, the maximum value on the color scale was set to the 99th quantile. Figures 15, 16, and 17 share a color scale.

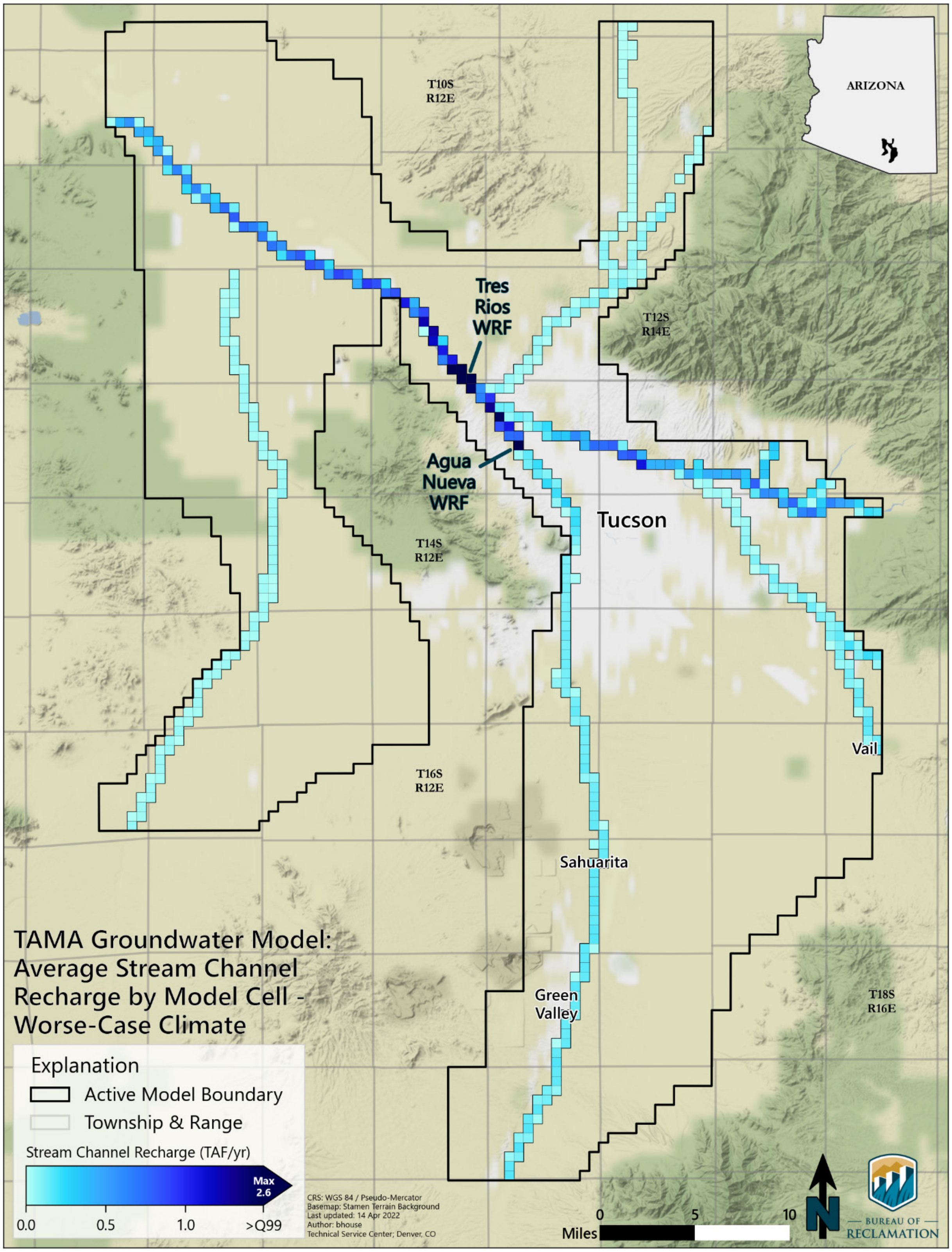

Figure 17. Average annual groundwater recharge from streamflow (both natural and reclaimed water) for the worse-case climate S-D scenarios (D, E, and F) over the projection period. For clarity, the maximum value on the color scale was set to the 99th quantile. Figures 15, 16, and 17 share a color scale.

2.2.4. Mountain Front Recharge

Mountain front recharge is implemented in the RCH. Mountain front recharge for the historical period (1940-2010) was estimated by Mason & Hipke (2013) during model development. Estimated mountain front recharge is spatially and temporally constant over the historical simulation period (Mason & Hipke, 2013). This does not include recharge due to seepage and infiltration from the major streams fed by runoff from the mountains discussed in the *Streamflow Infiltration* section of this Technical Memorandum.

The magnitude and spatial distribution of mountain front recharge are assumed to remain constant over the interim (2018-2019) and projection periods (2020-2060). Mountain front recharge rates for the historical simulation period (1940-2010) were extracted from the RCH input file developed by Mason & Hipke (2013). The RCH input file includes recharge from multiple sources. The location and rates of mountain front recharge were manually compiled using geographic information system (GIS) software and the map of mountain front recharge cells provided in Mason & Hipke (2013, Figure 21). In cells containing both mountain front and streamflow recharge, the mode of the simulated recharge for that cell was used—exploiting the fact that mountain front recharge is constant and during drier years no streamflow recharge occurs. This method resulted in a total of 28 TAF/yr of mountain front recharge with the spatial distribution indicated in Figure 18. This is consistent with what was reported in Mason & Hipke (2013) and was held constant for the interim and projection periods. This assumption is reasonable given its relatively small magnitude compared to other model inflows, it is consistent with the model configuration during calibration, and that changes in recharge from streams emanating from the major drainage basins is accounted for in streamflow infiltration.

2.2.5. Underflow from Adjacent Basins

Groundwater underflow into the TAMA Model domain occurs along the boundaries with SCAMA to the south, Altar Valley to the southwest, and Falcon Valley to the northeast (Figure 18). Underflow from each adjacent basin was estimated by Mason and Hipke (2013) during model development.

Underflows into the TAMA Model from Altar and Falcon Valleys are represented as constant fluxes of 10,200 and 70 acre-feet per year (afy), respectively. Underflow from these basins is implemented using the WEL. The spatial distributions and rates of underflow are held constant during the simulated historic period (1940-2010; Mason & Hipke, 2013). The historic distribution and rates of underflow developed by Mason & Hipke (2013) are also applied for the duration of the interim (2018-2019) and projection periods (2020-2060). This assumption is reasonable given its relatively small magnitude compared to other model inflows and its consistency with the model configuration during calibration,

Underflow into the TAMA Model from SCAMA is represented as a constant groundwater head boundary implemented using the Time-Varying Specified-Head (CHD) Package (Figure 18). The CHD Package allows flow across the boundaries to vary depending on the groundwater gradient between active model cells and constant-head cells. Mason & Hipke (2013) assigned varying values of head based on recent head contours of the area. The varying heads in the CHD allow for representing changes in groundwater heads in SCAMA, near the TAMA-SCAMA boundary. A CHD with an extended period was not available from ADWR.

This Study is focused within the TAMA and does not consider projections of groundwater conditions for adjoining basins. The most recent head values (2010) were held constant for the duration of the interim (2010-2019) and projection periods. This assumes that groundwater heads in SCAMA near the TAMA-SCAMA boundary remain consistent over the interim and projection periods. Underflow from SCAMA accounts for an average of 16 TAF/yr into the TAMA Model over the projection period. This assumption is reasonable given its relatively small magnitude compared to other model inflows.

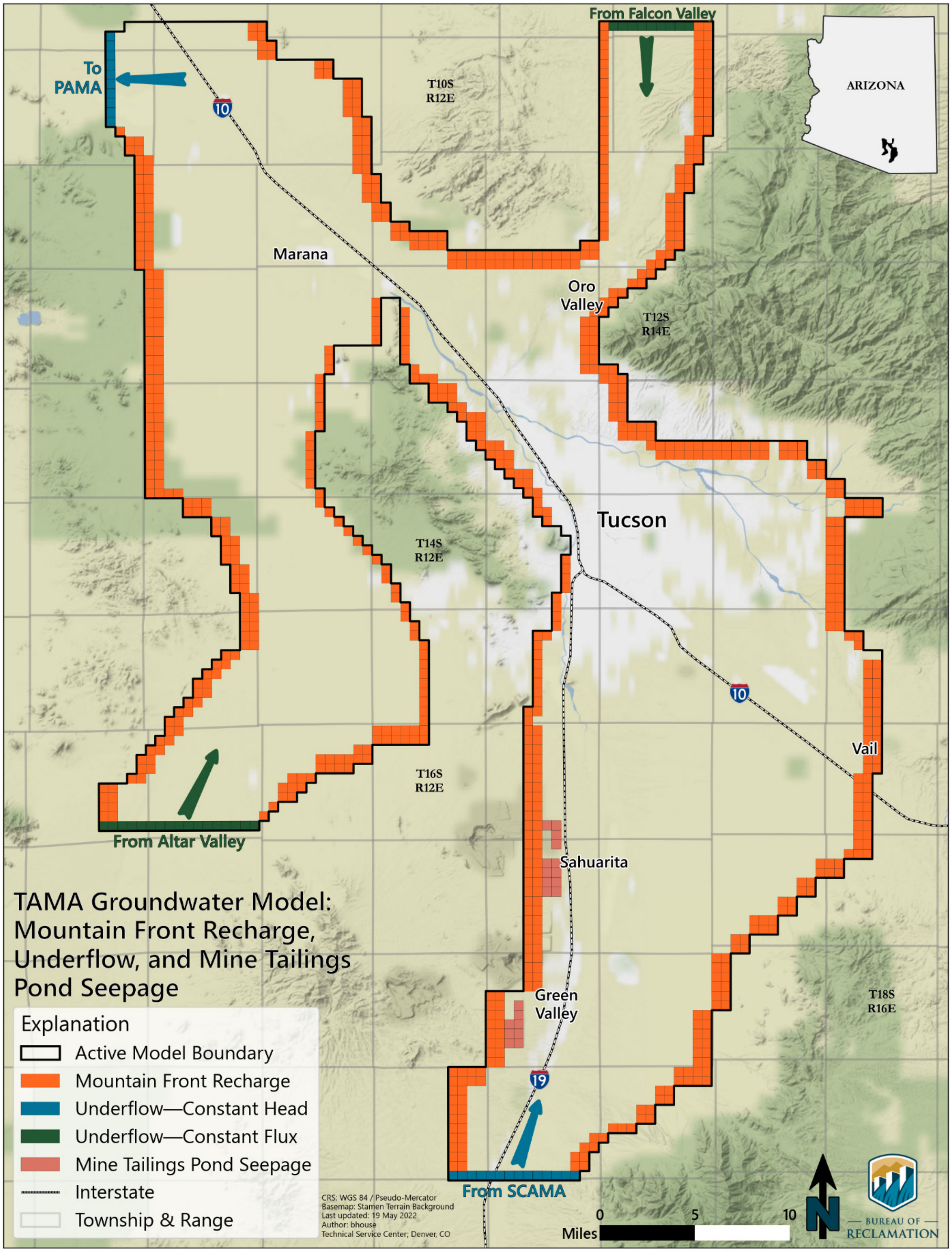

Figure 18. Constant flux and head inflows and outflows to the TAMA groundwater model. These include mountain front recharge, underflow to PAMA, underflow from SCAMA, underflow from Falcon Valley, underflow from Altar Valley, and mine tailings pond seepage.

2.2.6. Agricultural Deep Percolation

Irrigation of agricultural lands results in limited groundwater recharge from deep percolation of irrigation water past the plant root zone. The rate of deep percolation can be calculated based on the total irrigation water demand and irrigation efficiency by:

$$Deep\ Percolation = Total\ Irrigation\ (1 - Irrigation\ Efficiency)$$

In this case, total irrigation water demand is the volume of water used for irrigation, not the plant consumptive use. Based on discussions with the Study Partners and a site visit, a relatively high irrigation efficiency of 0.85 was applied for commercial agriculture and 0.65 for agriculture on tribal lands. Projections of agricultural irrigation water demands were provided by CAP for 2018-2060 in three groups: irrigation districts, irrigation grandfathered rights (IGFR), and irrigation on tribal agricultural lands (CAP, 2021).

CAP projects variations in irrigated acreage within irrigation districts under projected changes in climate and CAP supplies. Irrigated acreage varies with the available water supply, with more land being fallowed in years with lower supply and less in years with higher supply. CAP provided values for "irrigation intensity" by TAMA Model cell and irrigation district as an estimate of the amount of irrigation occurring within a given cell (CAP, 2021).

Projections of total annual agriculture irrigation water demands for four farms/irrigation districts, from 2018-2060, were provided for all S-D scenarios and include: BKW Farms, Cortaro-Marana Irrigation District, Farmers Investment Co., and Kai Avra. (Projections were also provided for Kai Red Rocks; however, these irrigated lands are located outside the TAMA Model domain.) Total deep percolation was subsequently calculated using an irrigation efficiency of 0.85 for all farms/irrigation districts. Deep percolation was then distributed over the TAMA Model cells based on the projected irrigation intensity of the farms/irrigation districts in a given cell. Based on Study Partner input, a constant 500 afy of agricultural demand was also applied at the Bridle Bit Ranch near Marana, AZ. Water is reported to be applied via sprinkler at this location. An irrigation efficiency of 0.7 was applied to this demand.

Projections of total annual agricultural irrigation water demands on tribal lands were also provided by CAP for the San Xavier and Schuk Toak Districts of the Tohono O'odham Nation (CAP, 2021). (Projections were also provided for Pascua Yaqui tribe; however, these irrigated lands are located outside the TAMA Model domain.) Total deep percolation from irrigation of tribal lands was then calculated using an irrigation efficiency of 0.65. Delineation of irrigated fields within the District boundaries was not attempted, and recharge was distributed based on the proportion of the overlapping District area with a given model cell. Only portions of the District located inside the active model domain were considered.

Some groundwater pumping within the TAMA occurs from wells having an IGFR and is assumed to be used for irrigation. Pumping projections for these wells were also provided by CAP (CAP, 2021). An irrigation efficiency of 0.85 was applied to these pumping projections to estimate deep percolation. The location of use was assumed to be near the well site, so recharge was applied to the model cell that the pumping well was located within.

Mason & Hipke (2013) employed an iterative method of temporally lagging the recharge to account for travel times through the vadose zone based on historical depth to groundwater. Sufficient details were not available to reproduce the iterative lagging method for this Study. Instead, the temporal lagging method applied to artificial recharge facilities was applied to recharge from agricultural deep percolation. This lagged the recharge over a three-year period applying 30% the first year, 40% the second, and 30% the final, third year (Mason & Hipke, 2013).

Total recharge from deep percolation of irrigation from these three sources (farms/irrigation districts, IGFR, and tribal agriculture) varies over S-D scenario from an average of 19.0 TAF/yr under scenario A to 20.3 TAF/yr under scenario D. Figure 19 presents the average spatial distribution of agricultural deep percolation across all S-D scenarios over the projection period. Recharge from agricultural deep percolation was implemented in the TAMA Model using RCH.

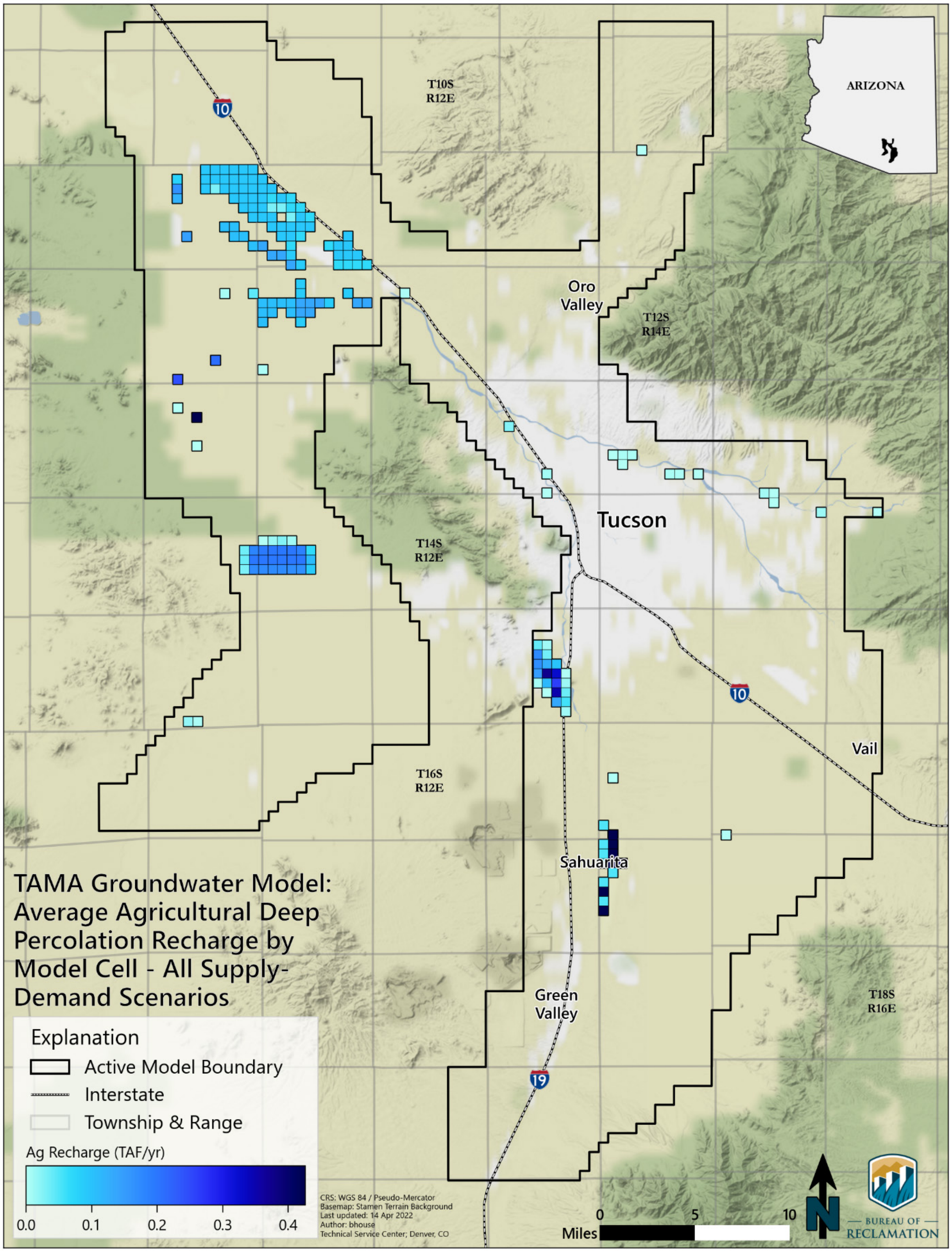

Figure 19. Average annual distribution of recharge from deep percolation of agricultural irrigation averaged over the projection period and S-D scenarios.

2.2.7. Mine Tailings Ponds Seepage

Seepage from mine tailings ponds contributes to groundwater recharge within the TAMA Model domain. This includes seepage from tailings ponds associated with the ASARCO Mission mine near the town of Green Valley and the Freeport-McMoran Sierrita mine near the town of Sahuarita. Seepage from tailings ponds has historically varied with the transitioning of mining operations in the area. Recharge from mine tailings ponds was estimated by Mason and Hipke (2013) during model development and is implemented using RCH. Recharge from tailings ponds over the interim (2018-2019) and projection periods (2020-2060) was assumed to be constant and equal to recharge from tailings ponds during the final year of the historical period. This results in a total of approximately 8 TAF/yr of recharge over the cells indicated in Figure 18.

2.2.8. Summary of Simulated Inflows

Inflows to the TAMA Model over the projection period are summarized in Table 5. Table 5 includes the range of inflows from the various sources across all S-D scenarios and the MODFLOW package that is used to simulate each inflow. The rate columns provide insight into the relative impact of changes to a given source of inflow on the groundwater model results.

Table 5. Summary of groundwater model inflows over the projection period and across all S-D scenarios. Development of each is described in the *Simulated Inflows* section of this Technical Memorandum.

Description	Rate (TAF/yr)			MODFLOW Package	Data Source(s)
	Min	Mean	Max		
Mountain Front Recharge*	-	28	-	RCH	Mason & Hipke (2013)
Underflow	27	28	29	WEL, CHD	Mason & Hipke (2013)
Mine Tailings Pond Seepage*	-	8	-	RCH	Mason & Hipke (2013)
Stream Channel Infiltration	54	121	382	RCH	Reclamation (2021), Mason & Hipke (2013), CAP (2021), Study Partners
Artificial Recharge Facilities	93	177	223	RCH	CAP (2021), Study Partners
Agricultural Deep Percolation	18	20	20	RCH	CAP (2021), Study Partners

*Inflow is constant over the projection period and across all S-D scenarios

The cumulative sum of groundwater inflows under each S-D scenario is shown in Figure 20. The apparent groupings of S-D scenarios in Figure 20 highlights the impact of climate on inflows (see Table 1). Cumulative inflows (recharge) under scenarios A, B, and C (current and best-case climates) are about 1.6 million acre-feet (MAF) greater over the projection period than under scenarios D, E, and F (worse-case climate). Differences between the current and best-case climates and the worse-case climate result in a difference in annual average recharge of about 40 TAF/yr over the projection period.

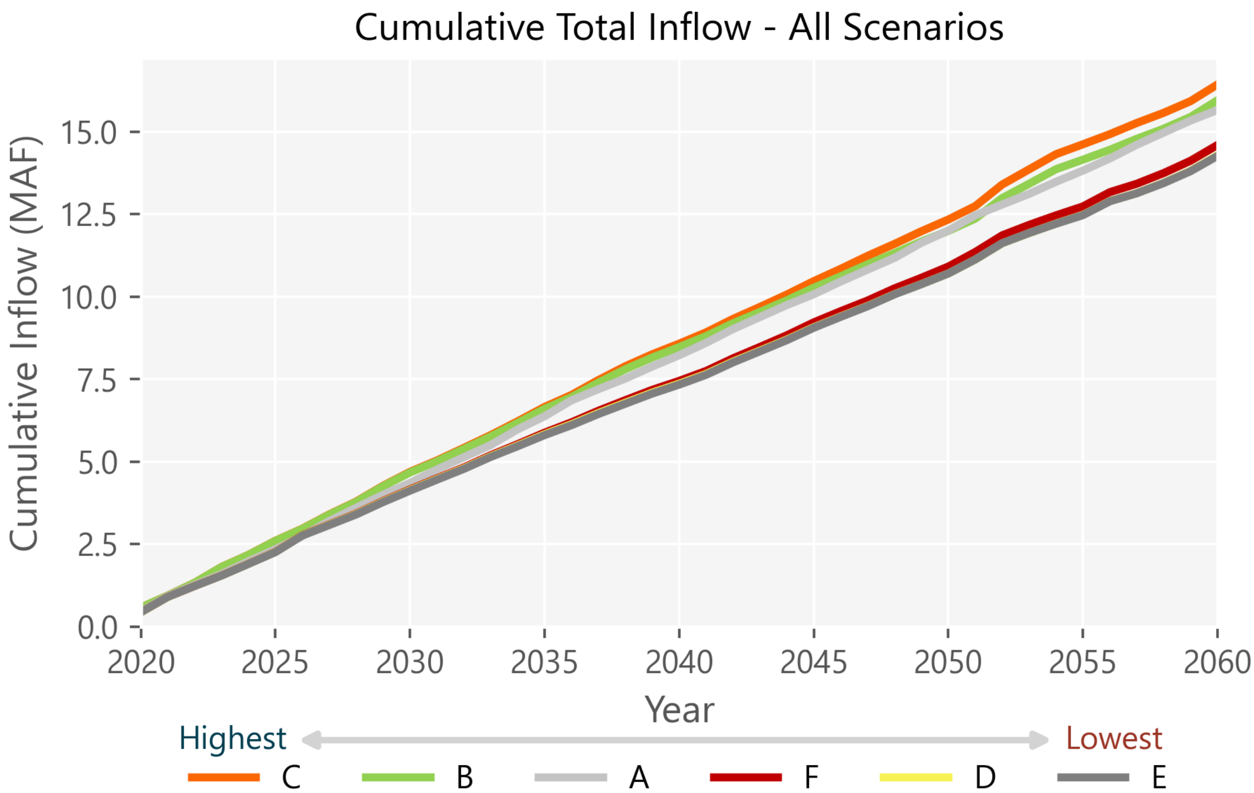

Figure 20. Cumulative sum of total annual simulated inflows to the TAMA groundwater model by S-D scenario.

Comparison of inflow projections between scenarios B and F provides insight into the range of risk to water resources covered by this Study. Scenario B combines the best-case climate with slow/compact demand growth and represents an S-D scenario with a lower risk to water resources; scenario F combines the worse-case climate with rapid/outward demand growth and represents an S-D scenario with a higher risk to water resources.

Recharge projections by source for these two S-D scenarios are shown in Figures 21 and 22. Shaded areas in Figures 21 and 22 represent the annual volume of recharge from a given source. From these figures it is evident that inflows from recharge facilities (violet area) and natural and reclaimed water streamflow infiltration (brown area) account for the majority of total recharge within the TAMA Model domain. The annual variability of streamflow infiltration recharge is also evident in both S-D scenarios (brown area). Annual variability in streamflow infiltration accounts for the majority of annual variability in total recharge. While difficult to observe at the scale of the figures, variability in agricultural deep percolation is present (red area) and has minimal impact on recharge to the TAMA as a whole.

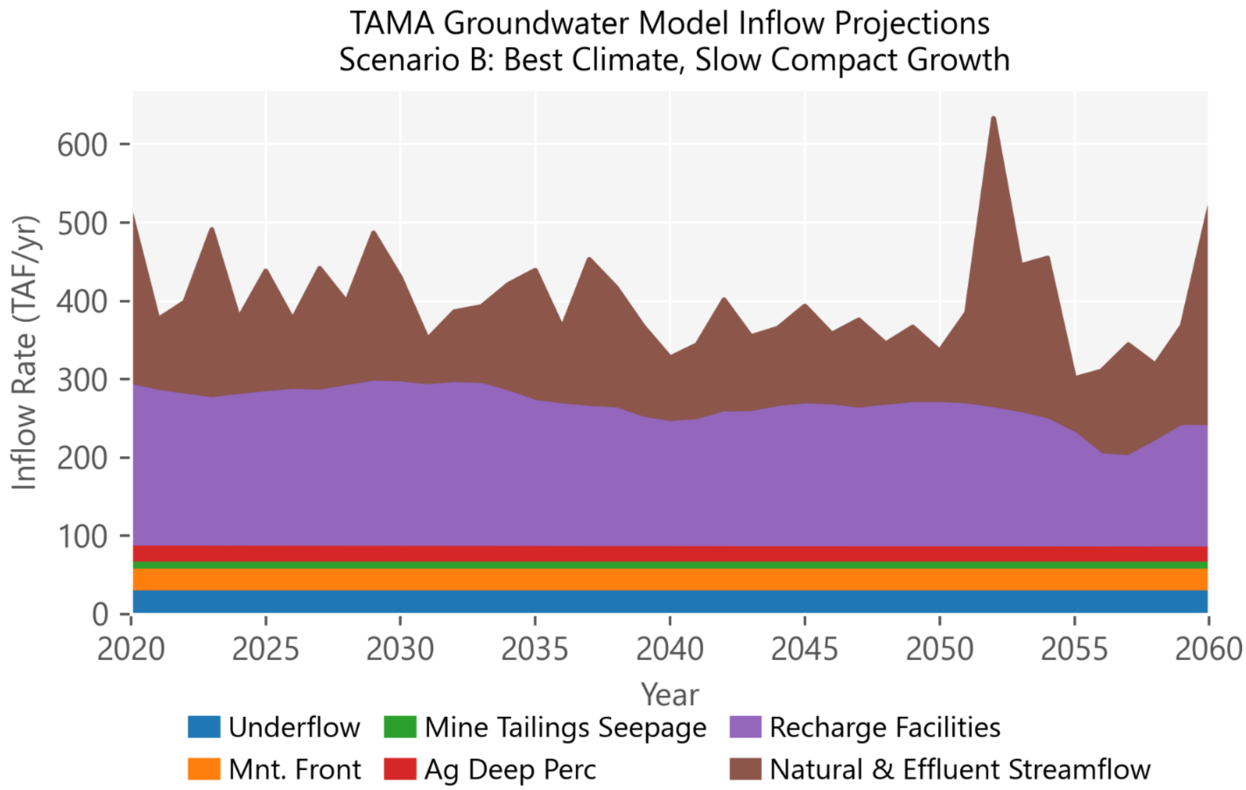

Figure 21. Inflow projections by type for the lower risk S-D scenario (B).

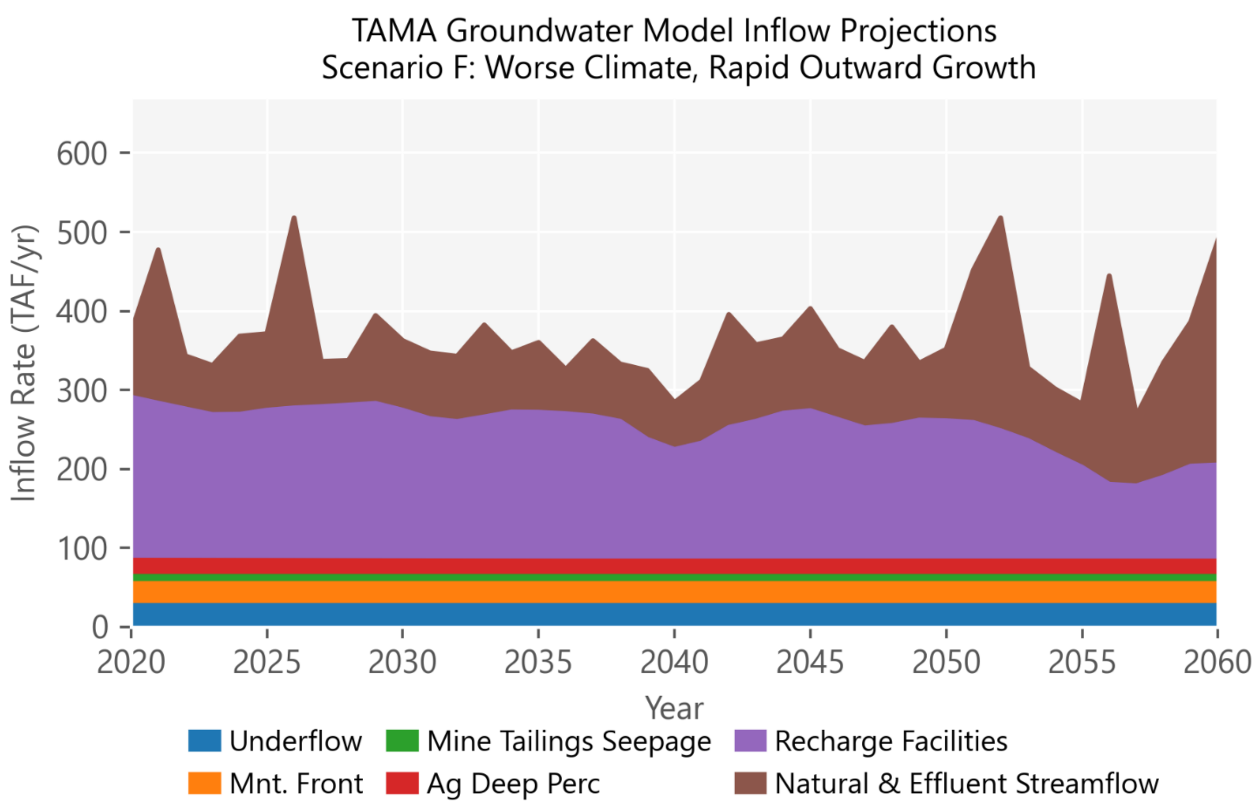

Figure 22. Inflow projections by type for the higher risk S-D scenario (F).

2.3. Simulated Outflows

Simulated outflows from the groundwater model (in order of descending magnitude) occur from: municipal pumping, agricultural pumping, mining pumping, underflow to an adjacent basin, industrial pumping, and evapotranspiration. Each will be discussed below.

2.3.1. Groundwater Pumping

Groundwater pumping constitutes the vast majority of outflow from the TAMA Model. From a low of about 70 TAF/yr in 1940, pumping reached a peak of over 400 TAF/yr in 1975. Pumping subsequently declined to about 280 TAF/yr in 2010—the final year of the simulation by Mason & Hipke (2013). Agricultural, municipal, and industrial uses are the major sectors of pumping, with agricultural pumping having declined significantly since the mid-1970s and municipal pumping steadily rising. Historical pumping was provided by ADWR for 1940-2017 (ADWR, 2019). From 1940 to 1983, pumping rates are informed by limited records and groundwater model calibration. Enactment of Arizona's Groundwater Management Act mandated reporting of annual pumping volumes to ADWR for recording. These reported volumes used by ADWR to assign pumping rates from 1984 to 2017.

Municipal Sector Pumping

Projections of municipal groundwater demands were generated by CAP for all S-D scenarios (CAP, 2021). Staff from local water providers (Study Partners) then distributed these demands to specific groundwater pumping wells. Most of these wells were already constructed, in the ADWR Wells 55 database[5], and assigned to cells in the TAMA Model. In cases where a new well was assigned pumping, a cadastral location was specified by the water provider, and the new well was assumed to be at the center of the finest cadastral discretization provided (e.g., section, sub-section, etc.). Layers were assigned to these new wells by comparison to other nearby wells of similar pumping capacity. Municipal pumping demands over the projection period range from an average of 152 TAF/yr under the slow/compact demand growth case to 184 TAF/yr under the rapid/outward demand growth case.

Agricultural Sector Pumping

Projections of farm/irrigation district agricultural pumping were provided by CAP for all S-D scenarios (CAP, 2021). Projections include pumping to meet water irrigation demands for BKW Farms, Cortaro-Marana Irrigation District, Farmers Investment Company, and Kai Avra. Demands were distributed between wells by CAP based on the historic pumping distribution. Projections of annual pumping demands for agriculture on tribal lands were also provided by CAP (CAP, 2021) for the San Xavier and Schuk Toak Districts of the Tohono O'odham Nation—though CAP does not project any pumping demand for the San Xavier District. (Projections were also provided for Pascua Yaqui tribe; however, these irrigated lands are located outside the TAMA groundwater model domain.) Study Partners did not assign projected agricultural pumping on tribal lands to specific wells; instead, pumping was distributed based on the proportion of the overlapping district area with a given model cell. Irrigated areas outside the TAMA Model domain were not considered. Agricultural pumping demands over the projection period range from an average of 51 TAF/yr under scenario A to 61 TAF/yr under scenario D.

[5] https://gisweb.azwater.gov/waterresourcedata/WellRegistry.aspx

Mining Sector Pumping

For the rapid/outward demand growth S-D scenarios (i.e., scenarios C and F), groundwater pumping associated with mining was increased over the projection period. Projections from CAP do not include mining demands. Instead, projections of mining pumping demands under the rapid/outward demand growth scenario included both an incremental increase of 30% by 2060 from the 2013-2017 mean pumping (or 0.75% per year) and a step increase of 5 TAF/yr starting in 2025 to meet demand for a new mine. Mining pumping demands over the projection period range from an average of 32 TAF/yr under scenarios A, B, D, and E to an average of 38 TAF/yr under scenarios C and F.

Other Pumping

The TAMA boundary does not coincide with the TAMA Model domain (Figure 3). The TAMA Model boundary covers portions of SCAMA to the south and PAMA to the northwest. Projections from CAP are applicable to the TAMA and do not cover pumping in these other areas. CAP projections also do not account for industrial, mining, turf grass, and some municipal demands. Therefore, additional pumping to fill these gaps was necessary for congruency between the historic, interim, and projection periods of the model. Using the 1940-2017 pumping data provided by ADWR, wells that were not included in the CAP projections, but had reported pumping in the previous three years, were assigned their five-year mean pumping for the final two years of the interim period (2018 and 2019) and for the duration of the projection period. Some exceptions were made in cases where all demand for a specific sector or water provider had been accounted for by CAP. This resulted in an additional 64 TAF/yr of pumping applied to the groundwater model over the projection period. Over half of this pumping is associated with mining operations.

Summary of Pumping

Annual groundwater pumping for all sources is shown in Figure 23 for the projection period. For context, the historical simulated pumping is also shown. The rapid/outward demand growth scenarios (C and F) show significant increases over the projection period and, by 2060, reach rates similar to the peak abstraction period of the mid-1970s. All other S-D scenarios suggest only modest rises in pumping demands compared to the historical 1940-1960 period—with the lower risk scenario (B) being approximately constant. None of the projections suggest a decline in groundwater pumping. The average spatial distribution of pumping, summed over model layers, across all S-D scenarios over the projection period is shown in Figure 24. The high pumping rates in Avra Valley near the CAVSARP and SAVSARP facilities indicate recovery of stored CAP water to meet municipal demands. Areas of high pumping demand in the Green Valley area to the south are primarily associated with mining operations.

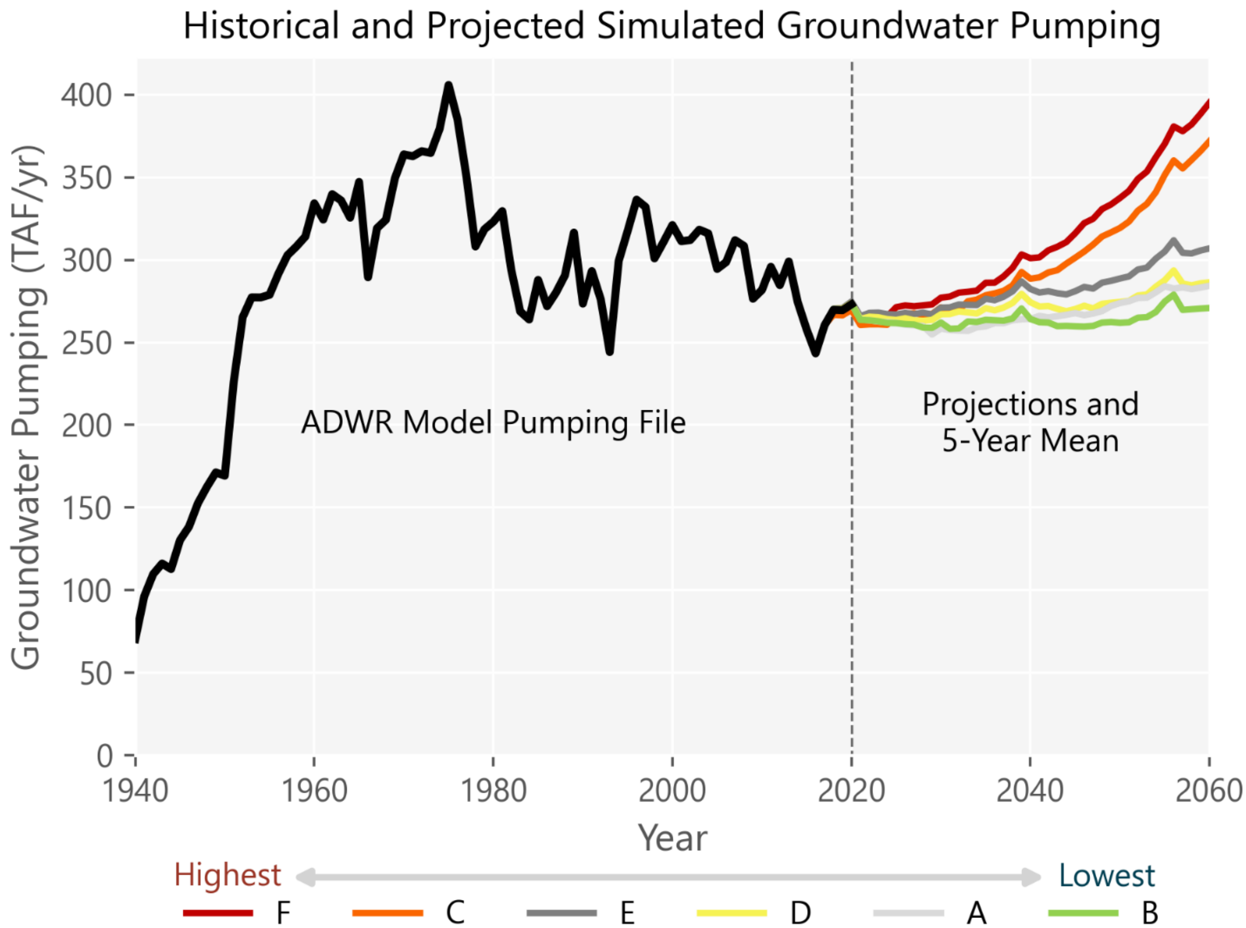

Figure 23. Historical and projected total annual groundwater pumping simulated in the TAMA Model.

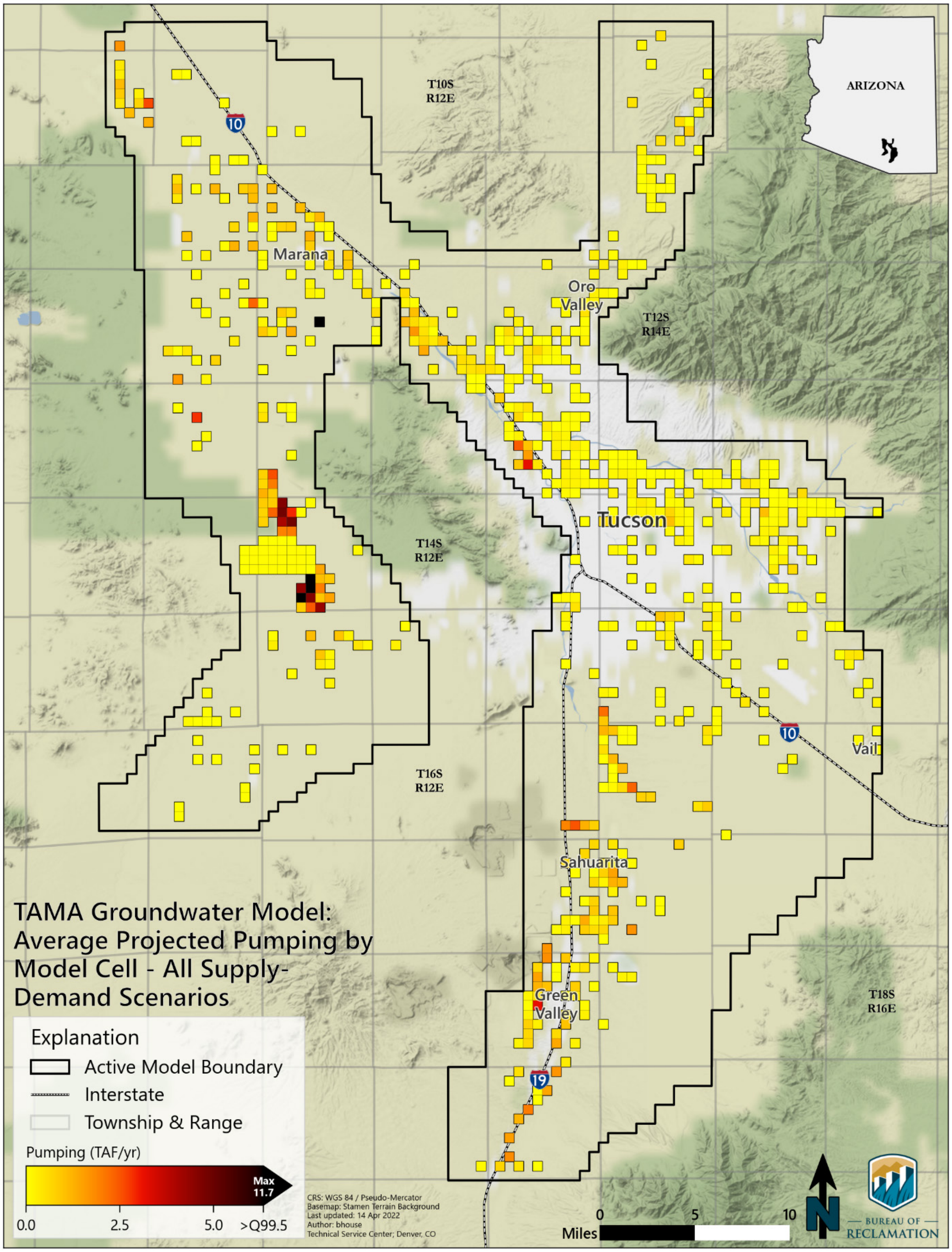

Figure 24. Average groundwater pumping by model cell over the projection period. Simulated pumping has been summed over the model layers. For clarity, the maximum value on the color bar was set to the 99.5th quantile.

Comparison of pumping projections between scenarios B and F provides insight into the range of risk to water resources covered by this Study. Scenario B combines the best-case climate with slow/compact demand growth and represents an S-D scenario with a lower risk to water resources; scenario F combines the worse-case climate with rapid/outward demand growth and represents an S-D scenario with a higher risk to water resources. Pumping projections by sector for these two S-D scenarios are shown in Figures 25 and 26. Shaded areas in Figures 25 and 26 represent the annual volume of groundwater pumping by each sector. Scenario B (Figure 25) maintains an almost constant pumping rate over the projection period, both overall and in within a given sector. Scenario F shows a significant, approximately 50%, increase in pumping. Most of this increase in projected pumping under scenario F is from the municipal sector (green area in Figure 26).

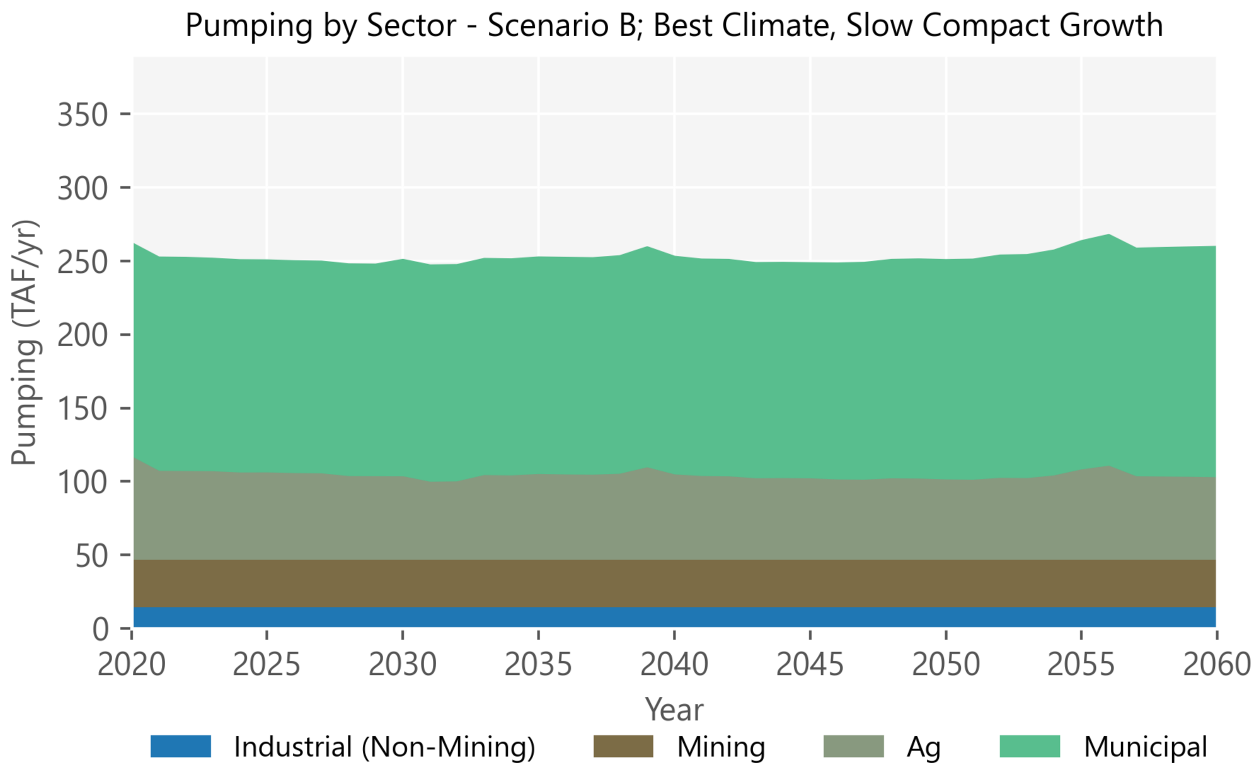

Figure 25. Pumping projections by water use sector for the lower risk S-D scenario (B).

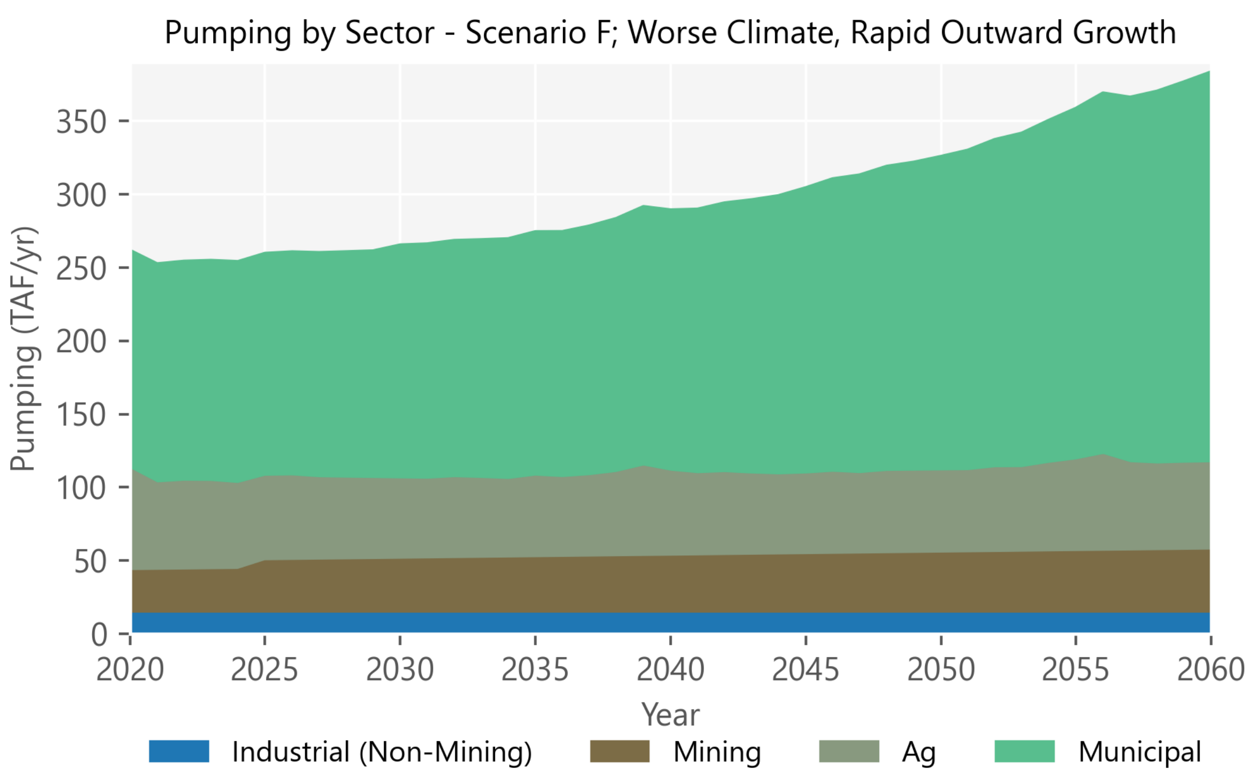

Figure 26. Pumping projections by water use sector for the higher risk S-D scenario (F).

After executing the groundwater model with the pumping projections described above, results indicated that there was insufficient groundwater to meet the applied pumping demands in some model cells. MODFLOW-NWT will automatically reduce groundwater abstraction to prevent model cells from going dry (Niswanger et. al., 2011). Mason & Hipke (2013) reported similar results during the historical modeled period. After discussion with Study Partners, it was decided that a likely course of action if a well were to go dry would be to construct a new, deeper well within a short distance of the existing well. To accomplish this, an iterative process was developed to shift a portion of the unmet pumping demand to a deeper layer and rerun the model.

This process was repeated until a minimum threshold of 10 TAF of total pumping reductions over the model period (1940-2060) was met. Even under the higher risk to water resources demand growth scenario (i.e., scenario F), the total pumping shift to lower layers was approximately 1% of the total applied pumping in a given year. Though the cause of unmet pumping demands may be due to overextraction, it is also possible (especially given the relatively small proportion of total demand) that this was due to limitations in the TAMA Model construction. This is supported by the fact that some unmet pumping also occurs in the historical period when actual pumping rates are applied.

2.3.2. Underflow to Pinal AMA

Underflow from the TAMA Model to PAMA is represented as a constant groundwater head boundary implemented using the Time-Varying Specified-Head (CHD) Package (Figure 18). The CHD Package allows flow across the boundaries to vary depending on the groundwater gradient between active model cells and constant-head cells. Mason & Hipke (2013) assigned varying values of head based on recent head contours of the area. The varying heads in the CHD allow for representing changes in groundwater heads in PAMA, near the TAMA-PAMA boundary.

A CHD with an extended period was not available from ADWR. This Study is focused within the TAMA and does not consider projections of groundwater conditions for adjoining basins. The most recent head values (2010) were held constant for the duration of the interim (2010-2019) and projection periods. This assumes that groundwater heads in PAMA near the TAMA-PAMA boundary remain consistent over the interim and projection periods. Underflow to PAMA accounts for an average of 20 TAF/yr out of the TAMA Model over the projection period.

2.3.3. Evapotranspiration

Evapotranspiration was included in Mason & Hipke (2013) along stream reaches where riparian vegetation is present. It is represented in the TAMA Model using the MODFLOW Evapotranspiration package (EVT). The input parameters are spatially and temporally constant over the historical simulation period. The locations and input parameters for the interim (2010-2019) and projection periods were unaltered from Mason & Hipke (2013) and held constant. In generally, evapotranspiration represents a minor portion of the overall groundwater budget and accounts for an average 4 TAF/yr over the projection period and all S-D scenarios.

2.3.4. Summary of Simulated Outflows

Outflows from the TAMA Model over the projection period are summarized in Table 6. Table 6 includes the range of outflows from the various sources across all S-D scenarios and the MODFLOW package that is used to simulate each outflow. The rate columns provide insight into the relative impact that changes to a given source of outflow have on the groundwater model results. Pumping across all sectors accounts for an average of 92% of total outflows simulated from the TAMA Model over the projection period and across all S-D scenarios.

Table 6. Summary of groundwater model outflows over the projection period and across all S-D scenarios. Development of each is described in the *Simulated Outflows* section of this Technical Memorandum.

Description	**Rate (TAF/yr)**			**MODFLOW Package**	**Data Source(s)**
	Min	**Mean**	**Max**		
Evapotranspiration	0.4	4	16	EVT	Mason & Hipke (2013)
Underflow	17	20	26	CHD	Mason & Hipke (2013)
Pumping – Municipal	145	166	268	WEL	Mason & Hipke (2013), CAP (2021), Study Partners
Pumping – Ag	47	57	70	WEL	Mason & Hipke (2013), CAP (2021)
Pumping – Mining	29	34	46	WEL	Mason & Hipke (2013), Study Partners
Pumping – Industrial (Non-Mining)*	-	13	-	WEL	Mason & Hipke (2013)

*Outflow is constant over the projection period and across all S-D scenarios

3. Supply-Demand Scenario Results

Predictive groundwater model runs were performed for each S-D scenario over the projection period using the TAMA Model (2020-2060; Table 1). Each S-D scenario was simulated by modifying model inputs to reflect projected changes in groundwater inflows and outflows as detailed above in the *Groundwater Model Updates* section of this Technical Memorandum (Section 2). Model results were evaluated to assess projected changes in groundwater heads and groundwater storage. Projected changes in groundwater heads and storage under future S-D scenarios are discussed below in Section 3.1. Results are then compared between S-D scenarios to analyze risk to water resources (Section 3.2), impacts of climate (Section 3.3), and impacts of demand growth (Section 3.4). Impacts of climate and demand growth are then compared in Section 3.5.

3.1. All Supply-Demand Scenarios

The LSCR Basin (TAMA) was in a state of overdraft throughout most of the historical period due to rising groundwater pumping and little augmentation from artificial recharge. Overdraft led to significant declines in groundwater heads and storage resulting in a cumulative groundwater storage deficit over 7 million acre-feet (MAF) by 2004 within the LSCR Basin. Implementation of artificial recharge projects and reductions in groundwater pumping allowed groundwater heads and storage to begin rebounding by the mid-2000s. By the end of the interim period (2019), groundwater storage had rebounded by more than 0.7 MAF, leaving about a 6.3 MAF deficit in storage since pre-development (Figure 27).

Simulated changes in groundwater storage over the projection period under each S-D scenario are shown in the right portion of Figure 27. Projected changes in groundwater storage exhibit a general grouping by climate scenario. Groundwater storage increases for all S-D scenarios through the end of 2030s. By 2060 scenarios A, B, and C (current and best-case climates) result in a notably greater increase in groundwater storage than scenarios D, E, and F (worse-case climate). Differences in demand growth are projected to have a larger impact during the later portion of the projection period. This is apparent from the separation between scenarios D, E, and F beginning around 2040 (Figure 27).

Under the higher risk to water resources S-D scenario (i.e., scenario F), approximately 0.9 MAF of groundwater storage replenishment occurs by the end of the projection period. While this higher risk S-D scenario is generally in overdraft for the final 10-years of the projection period, all other S-D scenarios are generally in surplus (Figure 27). This result suggests that under the range of water supply and demand growth considered in the S-D scenarios, the LSCR Basin as a whole has increasing groundwater storage throughout the projection period. However, this result does not mean that groundwater storage increases in all areas of the LSCR Basin; some areas exhibit declines in groundwater heads and storage while others experience increases.

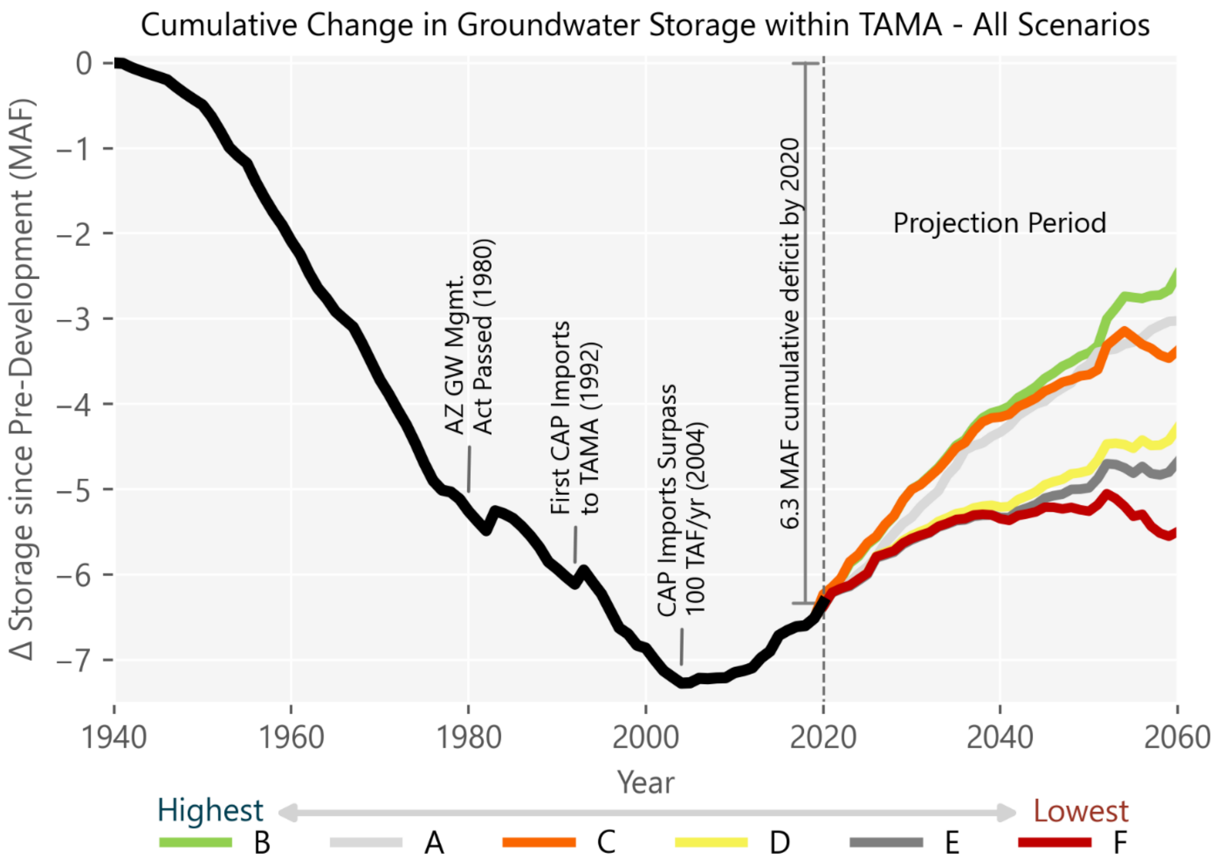

Figure 27. Simulated cumulative change in groundwater storage within the TAMA Model since pre-development (1940). Historical period is in black with results from S-D scenarios branching out at the start of the projection period (2020).

Maps of the simulated change in the groundwater table over the projection period—i.e., the difference in water table elevation between 2060 and 2020—provide insight into the spatial distribution of projected changes in groundwater heads and storage. Total hydraulic head of groundwater is a combination of both pressure from the weight of the water and the elevation of the water. For this Study, groundwater head can generally be considered to be the elevation of the water table. The spatial distribution of projected changes in groundwater heads under each S-D scenario is presented in Figure 28. The color scale is the same across all panels in Figure 28, with blue areas indicating an increase in groundwater levels and red areas indicating a decrease. Detailed, full-page maps of simulated change in groundwater head over the projection period for each S-D scenario are also included in Appendix B.

All panels of Figure 28 show blue shading near and along the Santa Cruz River (SCR) northwest of the Tucson metropolitan area, indicating rising groundwater levels in this portion of the LSCR Basin under all S-D scenarios. This is a result of increased infiltration of reclaimed water. Darker blue under scenarios B and C, compared to scenarios D, E, and F, represents the projected increases in streamflow in the Tanque Verde and Rillito Creek area under the best-case climate (Reclamation, 2021). Figure 28 also shows continued propagation of the mounds created by the recharge of CAP water at the CAVSARP and SAVSARP facilities in Avra Valley under all S-D scenarios. Consistent areas of rising groundwater levels under all S-D scenarios related to new recharge facilities are also depicted. Three new facilities (two of which have now begun operation) are included in the projections with: SHARP to the east, Project RENEWS in the Green Valley area, and the Santa Cruz Heritage Project in southwest Tucson (locations of these facilities are noted in Figure 7). Recharge of reclaimed water from the Green Valley WRF also contributes to the rise in the Green Valley area across all scenarios.

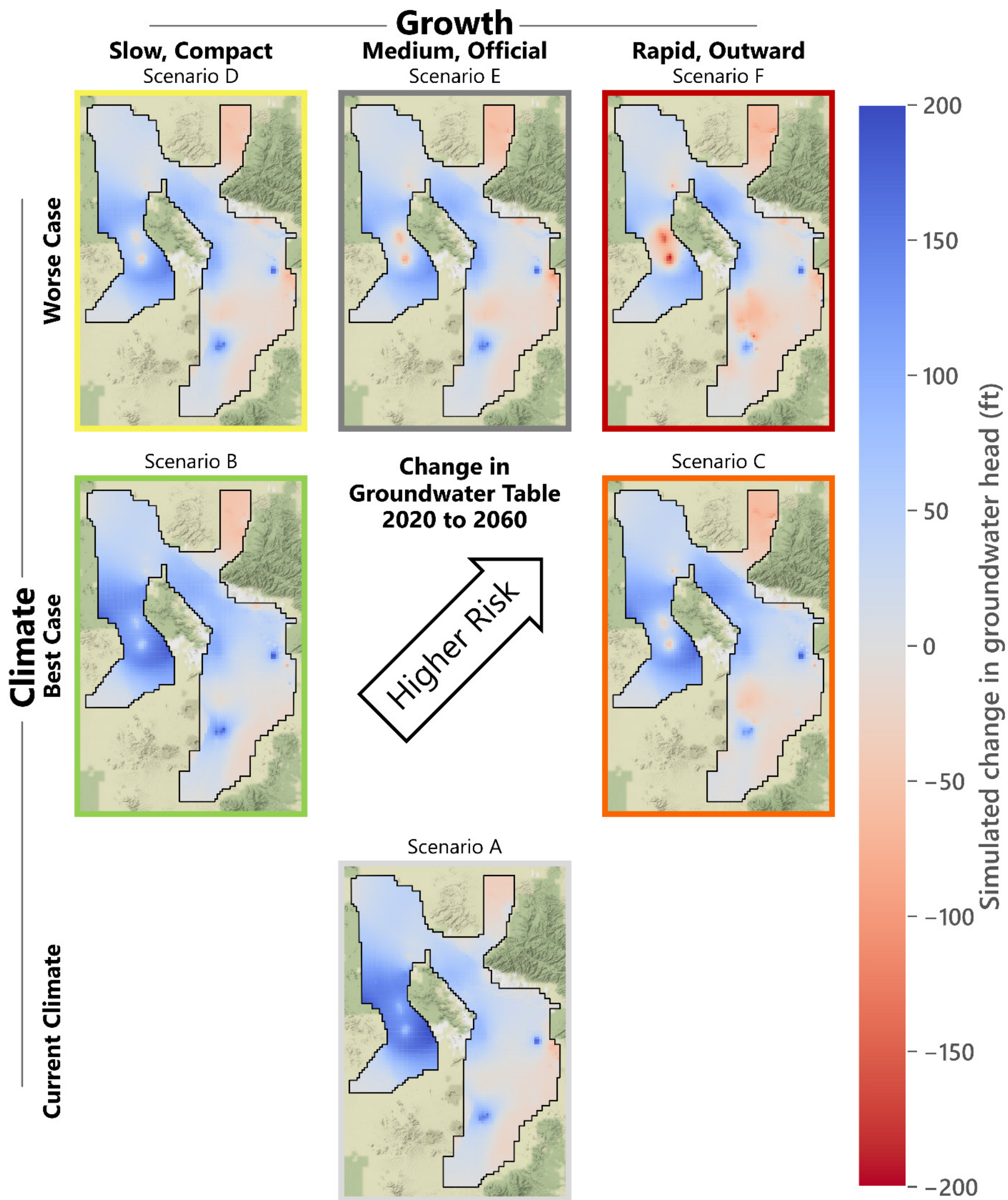

Figure 28. Change in simulated groundwater head by model cell over the projection period for each S-D scenario. Maps are positioned in the layout of Table 1. Color scale is shared between all maps.

3.2. Range of Risk to Water Resources

Of the S-D scenarios included in the Study, B has a lower risk to water resources and F has a higher risk. Comparison of these S-D scenarios provides insight into the range of future conditions considered in this Study. Figure 29 shows the simplified groundwater budgets and the annual change in groundwater storage for scenarios B and F. For simplicity, only major sources of recharge (all except underflow) and pumping (as on average it represents 92% of the total outflow from the model) are included in these figures. The yellow lines in the first and third panels of Figure 29 show annual recharge (inflow) to the TAMA Model and the blue lines show annual groundwater pumping (outflow) from the TAMA Model. When inflows exceed outflows, there is a surplus and water is added to groundwater storage (blue shaded area in second and fourth panels). When outflows exceed inflows, there is an overdraft and water is removed from groundwater storage (red shaded area of second and fourth panels).

For scenario B, pumping (blue line) is consistently less than recharge (yellow line) over the projection period, resulting in a consistent surplus (Figure 29). Under this scenario, overdraft only occurs during two years (2055-2056) when both streamflow infiltration and artificial recharge decline simultaneously, due to concurrent low streamflows and deeper CAP water shortages (Figure 21). Under scenario F, the steady increase in demand over the projection period results in pumping exceeding recharge by the last third of the projection period (Figure 29). Pumping in excess of recharge results in multiple years of overdraft, particularly towards the end of the projection period. However, during high streamflow years under the worse-case climate (2056, 2060), natural recharge exceeds these increased demands and results in surplus.

These results highlight the uncertainty in the range of plausible futures resulting from the Study, as well as the success of the historic water supply planning measures undertaken within the LSCR Basin. Even under the higher risk S-D scenario of this Study, projected annual overdraft is consistently less than historic overdraft, except for a few years during the last portion of the projection period.

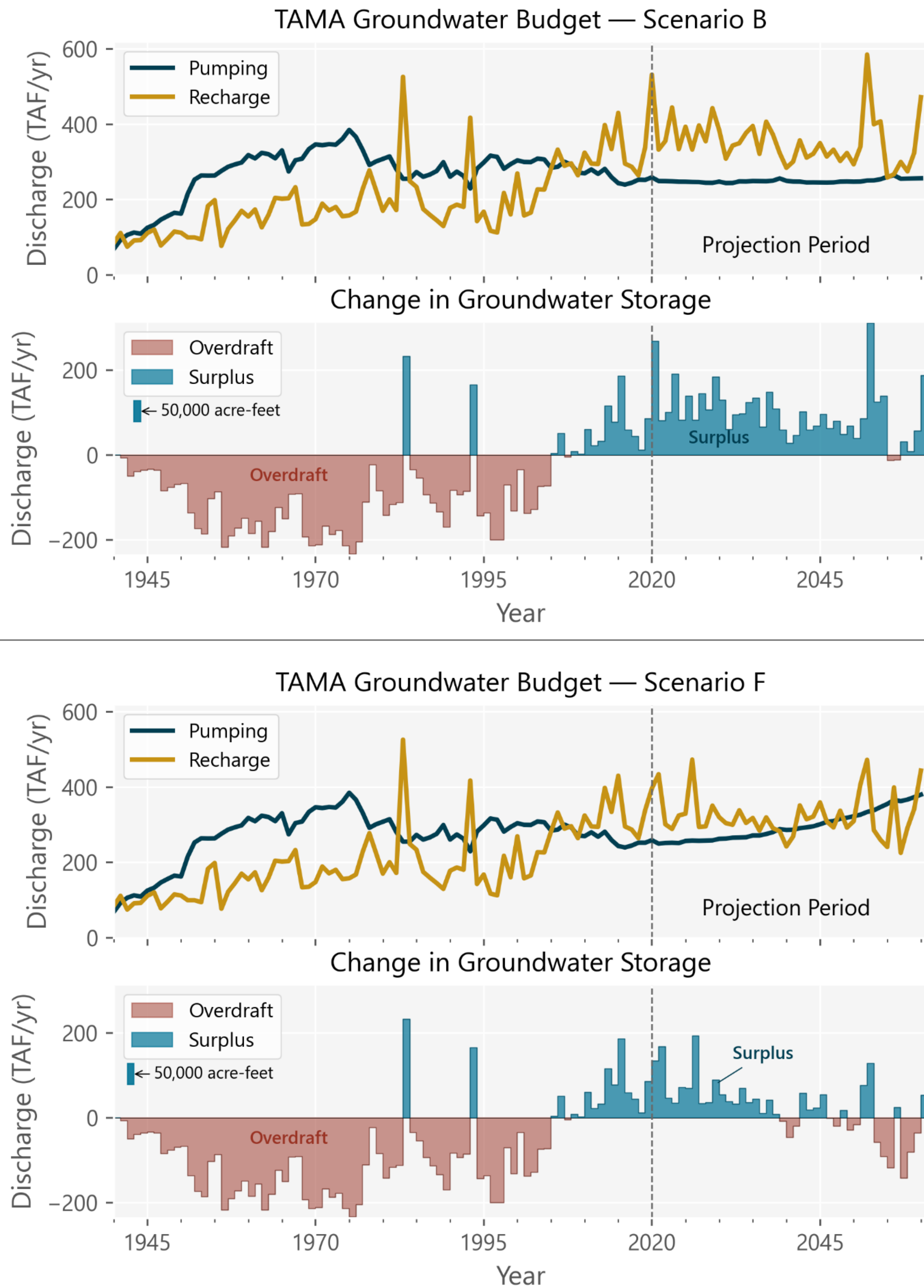

Figure 29. Simplified groundwater budget and change in storage for scenarios B (lower risk) and F (higher risk). Shaded areas (blue and red) are proportional to the volume of groundwater storage change (the area for 50,000 acre-feet is noted by the legend in blue).

In order to understand risk to water resources and identify effective adaptation strategies, it is important to consider the spatial distribution of changes in groundwater heads and storage. Figure 30 shows a map of the projected change in groundwater head over the projection period (2020-2060) under scenario F. Scenario F represents the S-D scenario with a higher risk to water resources considered in this Study and is expected to require the most adaptation. Areas of notable declines are labelled 1 to 5 in Figure 30. Each area is discussed below.

Area 1 in Figure 30 shows substantial declines in the groundwater table in the Cañada del Oro/Saddlebrook area, northeast of Oro Valley. Substantial declines result from the projected increase in pumping demand of about 50% by the end of the projection period combined with limited and intermittent recharge in this area.

The groundwater table in the Sabino Canyon and Tanque Verde area (Area 2) is also projected to decline slightly due to projected reductions in natural streamflow and corresponding streamflow infiltration. While small in magnitude, this decline is important because this location contains many of the LSCR Basin’s remaining riparian areas. Riparian areas support habitat for a wide variety of plants and animals and provide recreational and aesthetic values.

Area 3 in Figure 30 shows groundwater table declines in southeast Tucson. Declines in this area are largely driven by projected reductions in natural streamflow and increases in pumping demand for municipal supply. While the SHARP artificial recharge facility is projected to provide some additional recharge (facility location is shown in Figure 7), simulated recharge from SHARP does not propagate much to the southeast to offset the impacts of increased pumping and declining recharge.

Area 4 shows groundwater table declines in the Green Valley/Sahuarita area south of Tucson. Under scenario F, mining pumping is projected to increase in this area and recharge at the Pima Mine Road USF is projected to decrease due to reductions in available CAP supplies (facility location is shown in Figure 7). Natural streamflow in this area is also projected to decline during the initial 30 years of the projection period, followed by some recovery during the last 10 years. These factors combine to result in broad declines throughout the Green Valley/Sahuarita area.

Finally, Area 5 in Figure 30 shows substantial groundwater table declines in Avra Valley near the CAVSARP and SAVSARP facilities (facility locations are shown in Figure 7). These declines are a result of recovery of previously stored water from the CAVSARP and SAVSARP facilities. This area does not require adaptation as it is a result the facilities functioning as intended—water stored in the ground for later recovery. It does, however, indicate a projected decline in the stored groundwater available for future recovery.

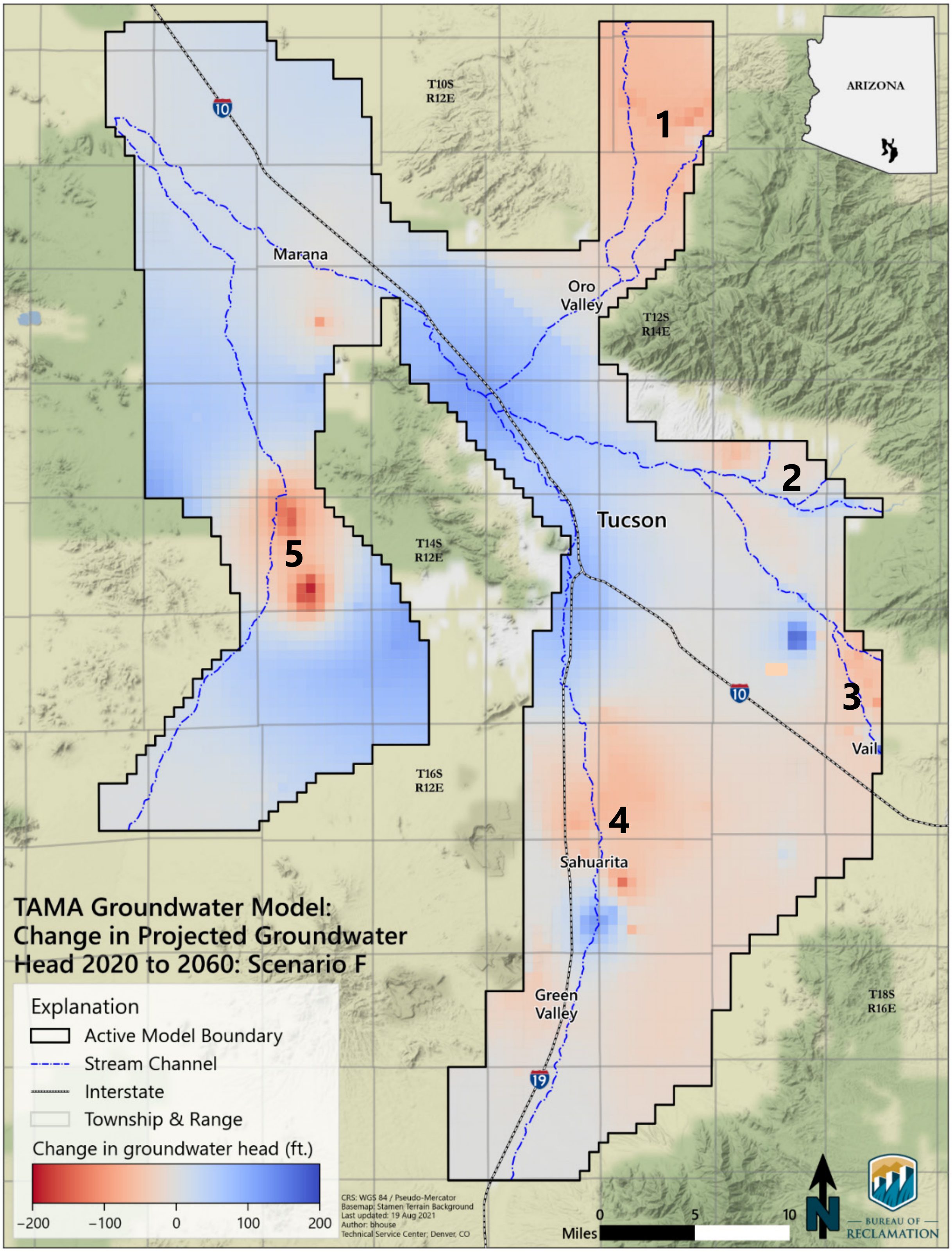

Figure 30. Change in groundwater head by model cell over the Study projection period (2020-2060) for scenario F (higher risk). Areas of general decline are labelled 1 to 5 and are discussed in the text.

3.3. Climate Impact

The contribution of future climate to the projected changes in groundwater heads and storage can be evaluated by comparing results for scenarios C and F. Both S-D scenarios reflect rapid/outward demand growth, with scenario C incorporating the best-case climate and scenario F incorporating the worse-case climate. Differences in the projected groundwater heads and storage between these S-D scenarios reflect the influence of climate assumptions on projected groundwater conditions. Comparison of scenarios B and D also isolates the influence of climate. This comparison yielded similar differences in projected groundwater heads and storage.

Figure 31 shows the difference in projected groundwater heads for the last year of the projection period (2060) between scenarios C and F. Blue shading in Figure 31 indicates areas where the projected groundwater table under scenario C (best-case climate) is higher than under the scenario F (worse-case climate). Red shading indicates areas where the projected groundwater table is higher under scenario F. Climate impacts both local streamflow and availability of Colorado River water for importation via the CAP. The difference in simulated groundwater head between scenarios C and F reflects both of these impacts.

The blue-shaded areas in Avra Valley near the CAVSARP and SAVSARP facilities are simulated to receive identical recharge from natural streamflow in Brawley Wash (see the *Streamflow Infiltration* section of this technical memorandum for further explanation). Differences in groundwater levels in the Avra Valley are therefore due to climate-driven differences over the entire Colorado River Basin, which results in different levels of CAP deliveries under the best-case and worse-case climates.

CAP deliveries under each of the climate scenarios analyzed here are based on projections of supply for the overall Colorado River Basin (CAP, 2021). The volume of CAP water available for recharge at the CAVSARP and SAVARP facilities is approximately 0.5 MAF greater over the projection period under the best-case climate than under the worse-case climate. More CAP water is also available to meet demands under the best-case climate, which reduces the need for recovery of stored groundwater. Thus, the impacts of climate over the entire Colorado River Basin water supply is the predominate driver of the higher groundwater heads in the Avra Valley under scenario B.

In contrast to the Avra Valley, blue-shaded areas in the vicinities of Green Valley/Sahuarita, Vail, and Tanque Verde in Figure 31 are predominately driven by greater recharge from natural streamflow under the best-case climate (scenario B) compared to the worse-case climate (scenario F). The best-case climate exhibits greater runoff in this portion of the LSCR Basin, which results in greater groundwater recharge from natural streamflow. This additional streamflow recharge under the best-case climate offsets increased pumping to meet rising municipal and mining demands in these areas.

The best-case climate reflects lower future greenhouse gas (GHG) concentrations (RCP 4.5) whereas the worse-case climate reflects higher future GHG concentrations (RCP 8.5). The difference in the streamflow and water availability between these climate scenarios impacts projected groundwater heads and storage over large swaths of the Study area (Figure 31). Notably, impacts within the Study area reflect the effects of climate conditions on local streamflow within the LSCR Basin as well as streamflow and water availability within the broader Colorado River Basin (in the form of CAP supplies). These results suggest that the future of groundwater supplies within the LSCR Basin depends not only on climate changes within the Study area, but also on changes for the Colorado River Basin as a whole. In other words, the water supply future of the LSCR Basin is linked to that of the Colorado River Basin as a whole through the importation of Colorado River water via the CAP.

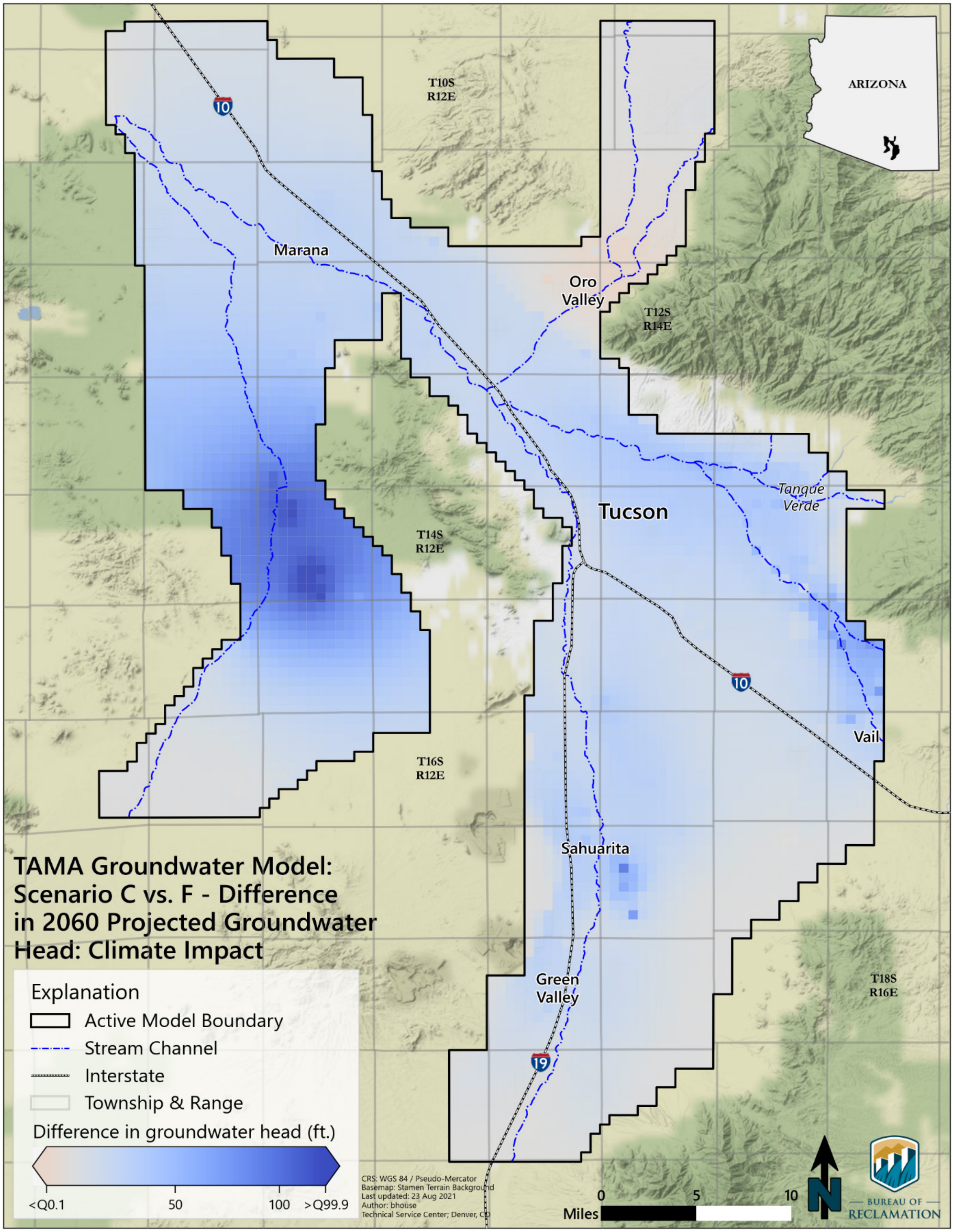

Figure 31. Difference in simulated head between scenarios C and F at the end of the projection period (2060). Map shows the spatial impact of the different climate scenarios (best-case vs. worse-case climates). Blue shading are areas where scenario C heads are higher than F—vice-versa for red. For clarity, the minimum and maximum values on the color scale were set to the 0.1 and 99.9th quantile, respectively.

3.4. Demand Growth Impact

The impact of demand growth assumptions on the projected changes in groundwater heads and storage can be evaluated by comparing results for scenarios D and F. Both S-D scenarios reflect the worse-case climate, with scenario D representing slow/compact demand growth case and scenario F representing the rapid/outward demand growth case. Differences in projected groundwater heads and storage reflects the influence of assumptions regarding future demand and growth patterns on projected groundwater conditions. Comparison of scenarios B and C also isolates the influence of demand growth. This comparison yielded similar differences in projected groundwater heads and storage.

Figure 32 shows the difference in projected groundwater heads for the last year of the projection period (2060) between scenarios D and F. Blue shading indicates areas where the projected groundwater table is higher under scenario D; red shading indicates areas where projected groundwater table is higher under scenario F.

Groundwater heads along the SCR northwest of Tucson are greater under scenario F (rapid/outward demand growth) compared to scenario D (slow/compact demand growth; red-shaded areas in Figure 32). This is due to increased population and municipal water use under the rapid/outward demand growth case, which results in increased discharge of reclaimed water to the SCR. The increase in WRF discharges to the SCR is illustrated in **Error! Reference source not found.** for the SCR reach above the Cortaro gage. Increased discharge of reclaimed water results in increased groundwater recharge. This increase in recharge along the SCR northwest of Tucson results in higher groundwater heads in this area. Additional groundwater is largely recovered from Avra Valley to meet the greater municipal demand under scenario F. These locations are hydrogeologically disconnected. The additional groundwater recovery does not impact this area.

Figure 32 shows higher groundwater levels under scenario D compared to scenario F (blue-shaded areas) in the Avra Valley near the CAVSARP and SAVSARP recharge facilities. These facilities receive nearly identical volumes of recharge over the projection period under scenarios D and F. However, higher water demands under scenario F (rapid/outward demand growth) result in greater recovery of stored groundwater from these facilities to meet those demands. By the end of the projection period, the amount of groundwater recovered from the CAVSARP and SAVSARP facilities under scenario F is approximately double the amount recovered under scenario D. This difference in recovery between scenarios D and F demonstrates that these facilities are functioning as intended—artificially recharged water is being recovered to meet demands within the LSCR Basin when other water supplies are not available.

The Green Valley/Sahuarita area is also projected to have higher groundwater heads under scenario D (slow/compact demand growth) compared to scenario F (rapid/outward demand growth). Two active mines are located in this area. Under scenario F, pumping to meet mining demands is projected to increase 30% above current rates by the end of the projection period. Scenario F also includes groundwater pumping to meet demands for a new mine. Under scenario D, pumping to meet mining demands is projected to remain constant for the duration of the projection period. Scenario D incorporates lower projections of population growth than in scenario F.

Scenario D also incorporates lower projections of population growth than in scenario F. Pumping to meet municipal demands for the Green Valley/Sahuarita area are projected to more than double by the end of the projection period under scenario F (CAP, 2021). Higher groundwater heads in the Green Valley/Sahuarita area under scenario D are therefore due to lower pumping rates for the mining and municipal sectors. It should be noted that the TAMA groundwater model is known to not perform as well in this area and is undergoing some structural changes for the next update by ADWR (Nelson & Clark, 2020). The spatial distribution of differences in the groundwater heads in this area is therefore better interpreted as a general difference over the area then as cell-specific changes.

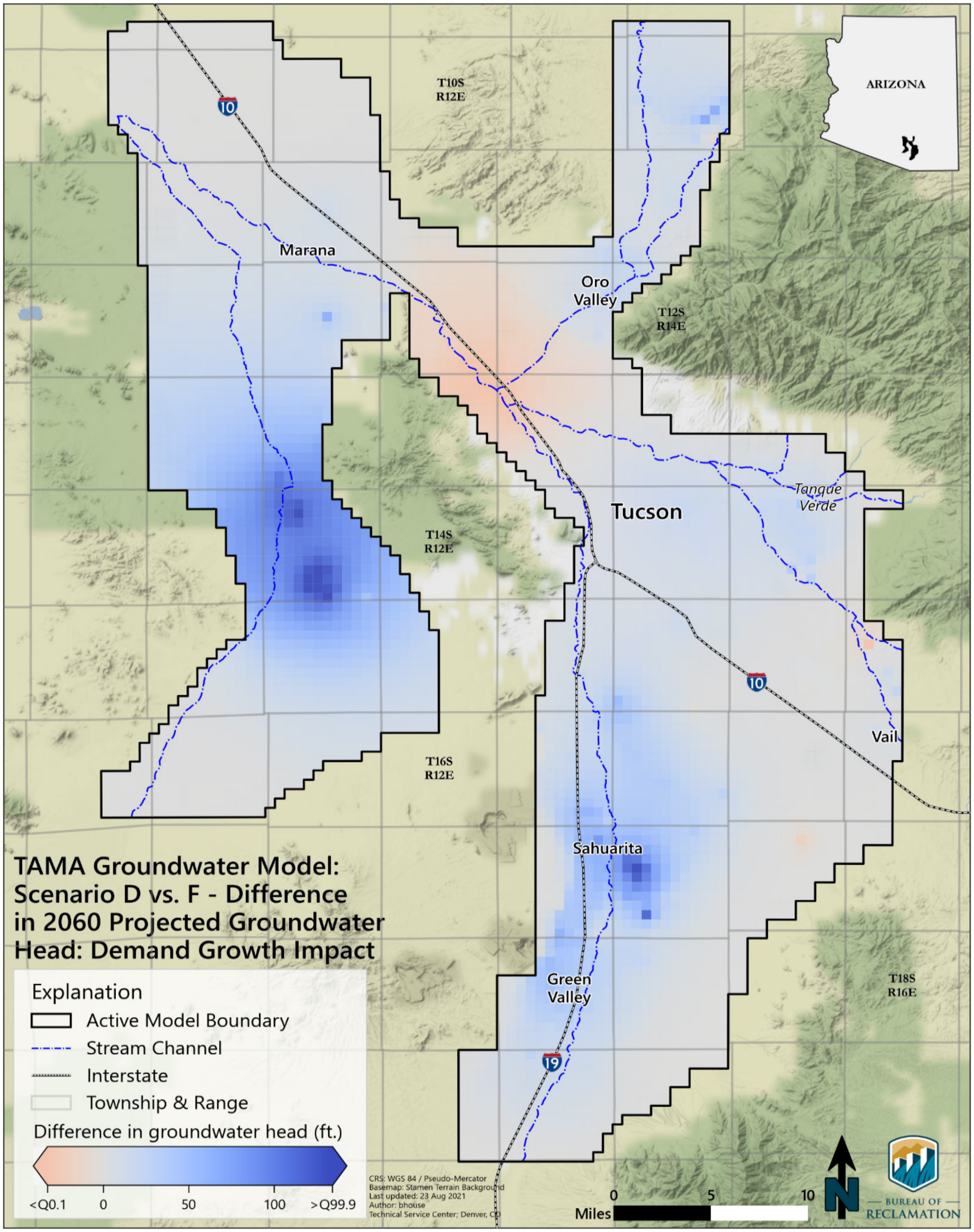

Figure 32. Difference in simulated head between scenarios D and F at the end of the projection period (2060). Map shows the spatial impact of the different demand growth cases (slow/compact vs. rapid/outward). Blue shading are areas where scenario D heads are higher than F—vice-versa for red. For clarity, the minimum and maximum values on the color scale were set to the 0.1 and 99.9th quantile, respectively.

3.5. Climate vs. Demand Growth Impact

The relative impacts of climate and demand growth on projected groundwater storage can be evaluated by comparing results from scenarios B, D, and F. Scenarios B and D share the same demand growth scenario (slow/compact) but different climate scenarios (best-case for scenario B, worse-case for scenario D). Scenarios D and F share the same climate scenario (worse-case) but different demand growth scenarios (slow/compact for scenario D, rapid/outward for scenario F).

Cumulative changes in groundwater storage under scenarios B, D, and F are illustrated in Figure 33. Results indicate that future climate conditions have a greater impact on projected groundwater storage than future demand growth (Figure 33). The difference between scenarios B and D (green area) increases more rapidly than the difference between scenarios D and F (yellow area), suggesting that differences in climate would have an impact sooner than differences in demand growth. By the end of the projection period, about 60% of the range of projected change in groundwater storage is due to the influence of the climate scenario. This result reflects impacts of climate on both local runoff and on water availability within the broader Colorado River Basin. The remaining 40% of the range is due to the difference in demand growth scenario.

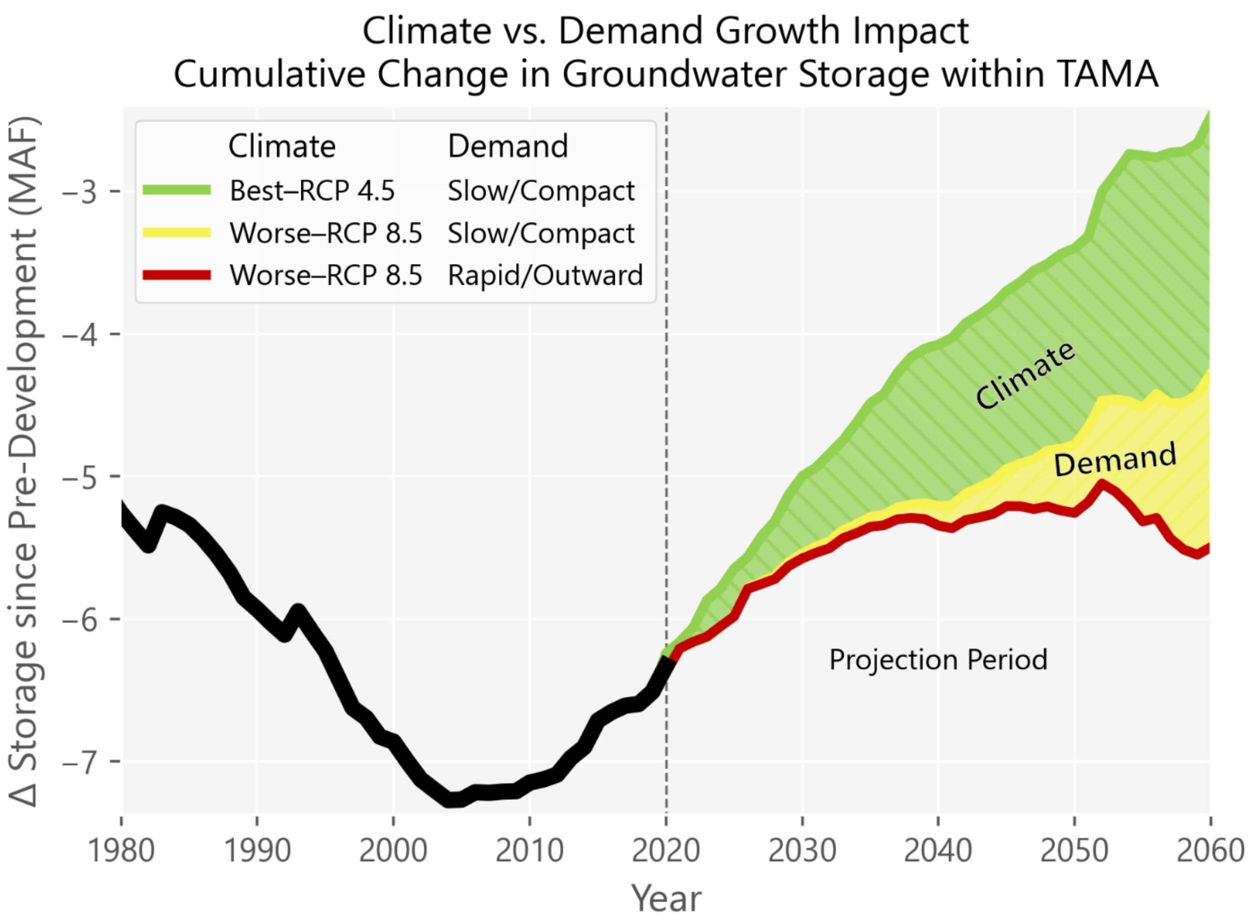

Figure 33. Simulated cumulative change in groundwater storage within the TAMA Model since pre-development (1940) for scenarios B, D, and F. Historical period is in black starting at 1980 (40 years post commencement of the simulation). The difference between scenarios B and D represents the impact of climate, while the difference between scenarios D and F represents the impact of demand growth.

4. Adaptation Strategies

As discussed above in Section 3, groundwater storage and heads are projected to decline in several portions of the LSCR Basin. Areas where adaptation strategies may be necessary to mitigate projected declines were identified based on the S-D scenario with the higher risk to water resources (i.e., scenario F) and Study Partner direction. Projected changes in the groundwater table under this S-D scenario are illustrated in Figure 30. Areas identified as potentially requiring adaptation strategies include: the Cañada del Oro/Saddlebrooke area northeast of Oro Valley; the Sabino Canyon and Tanque Verde area east of Tucson; southeast Tucson; and the Green Valley/Sahuarita area south of Tucson.

Study Partners developed fifteen adaptation strategies to mitigate the impacts of future climate and demand growth on water supplies in the Study area (Reclamation, 2022). Eleven of these strategies targeted a specific area of supply/demand imbalance listed above. Some of these adaptive strategies assume additional supplies of CAP water being delivered to the LSCR Basin. The origin of these additional supplies is not defined in this Study. Five of these adaptation strategies were appropriate for simulation in the TAMA Model and are summarized in Table 7. These adaptation strategies focused on the Cañada del Oro/Saddlebrooke and Green Valley/Sahuarita areas.

Table 7. Adaptation strategies evaluated in the TAMA Model (LSCR Basin Study Partners, 2021).

Strategy ID	Rate (TAF/yr)	Strategy Name	Brief Description
CDO-1	5	CAP Supplies to CDO In-stream Recharge	Pipeline and pump stations to convey additional water from the CAP Red Rock Pumping Plant to Cañada del Oro (CDO) Wash area for in-stream recharge.
CDO-2	10	SCR Reclaimed to CDO In-Stream Recharge	Pipeline to convey reclaimed water flowing out of the LSCR Basin from the Santa Cruz River (SCR) to the CDO Wash area for in-stream recharge. Includes treatment for PFAS and 1,4 dioxane.
CDO-3	1.12	Saddlebrooke Sub-regional WRF with In-stream Recharge	Saddlebrooke sub-regional WRF and pipeline for in-stream recharge to CDO. WRF would have 1 million gallon per day (MGD) capacity.
GV-1	10	CAP Supplies to FICO Continental Farms (pecan orchards)	Extend Farmers Investment Company (FICO) Groundwater Savings Facility (GSF) pipeline to convey CAP water to additional pecan orchards in lieu of irrigation with groundwater.
GV-2	2	CAP Supplies to Canoa Ranch Recharge via FICO Pipeline Extension	Extend FICO GSF pipeline to Canoa Ranch for in-stream or basin recharge in the winter months (when not needed for irrigation).

Adaptation strategies CDO-1, CDO-2, CDO-3, and GV-2 include discharge into a stream channel at a strategic location. GV-1 involves the use of CAP water in lieu of groundwater pumping for irrigation at the FICO pecan orchards over and above what has already been planned. GV-2 would extend the pipeline bringing CAP water to the FICO orchards southward to Canoa Ranch. CAP water would be recharged in this area seasonally, when the pipeline was not being used for agricultural irrigation.

Each of these strategies was simulated individually with the TAMA Model by modifying the model input files to include a new inflow (recharge) or to reflect reduced groundwater pumping. Additional recharge was represented as a constant inflow over the projection period (2020-2060). Reduced groundwater pumping was represented as a reduction in annual pumping rates. All strategies were simulated under scenario F, which reflects the worse-case climate and rapid/outward demand growth scenario.

For CDO-1 and 2, water would be conveyed for discharge into Big Wash (location noted in Figure 8) and would contribute to streamflow infiltration along this reach. CDO-3 involves the construction of a new WRF in the area to serve future development, with the discharge of reclaimed water at the same location as in CDO-1 and CDO-2. Equation 1 was used to distribute the added streamflow infiltration along the channel (Burkham, 1970).

For GV-1, approximately 10 TAF/yr of additional CAP supplies would be made available beginning in 2027 for irrigation on the FICO Sahuarita Farm in lieu of pumping. The existing FICO CAP Line, LLC (FCAP) pipeline would be extended to convey CAP water to portions of the farm currently irrigated with groundwater. Groundwater pumping rates would be reduced accordingly. The CAP supplies would be a combination of water already being imported into the LSCR Basin and new supplies imported by FICO storage partners. Reduced pumping rates for GV-1 were provided by Study Partners.

Under GV-2, the existing pipeline conveying CAP water to the FICO Sahuarita Farm would be extended southward approximately 10 miles to provide 2 TAF/yr for infiltration into the SCR at the Canoa Ranch south of Green Valley. This additional water would be conveyed during the irrigation off-season.

The potential benefit of each adaptation strategy on the LSCR Basin water supply was evaluated based on the difference in the groundwater table between simulations of scenario F with and without the adaptation strategy. Figures 34 to 38 illustrate the extent of the LSCR Basin where each strategy would result in an increase in groundwater table of one foot or greater for the final year of the projection period (2060). Note: Results shown in Figures 34 to 38 represent the projected benefit of each adaptation strategy if the strategy was implemented for the duration of the projection period (e.g., under CDO-1, 5 TAF/yr being discharged into Big Wash for 40 years).

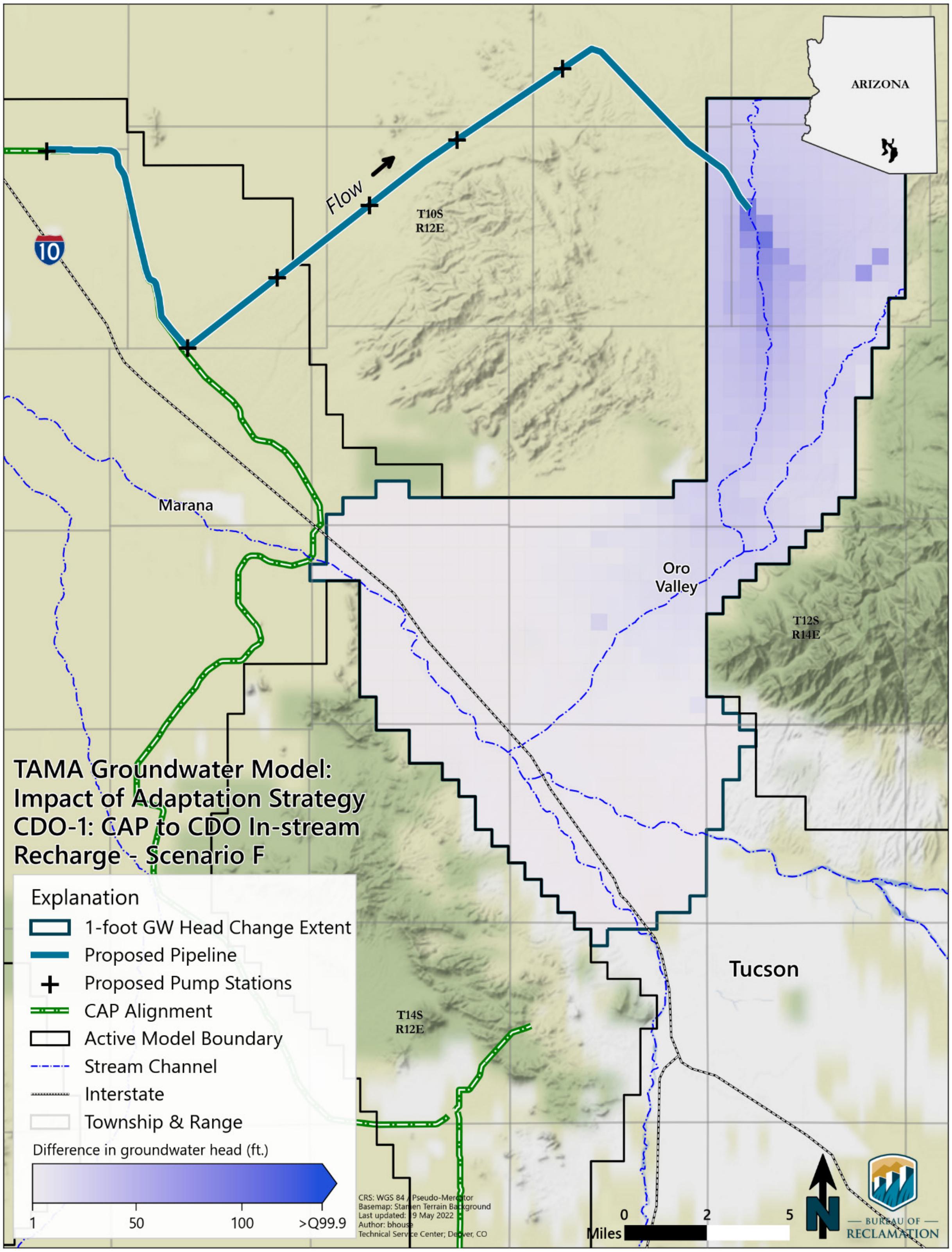

Figure 34. Difference in the simulated groundwater table for scenario F with inclusion of adaptation strategy CDO-1. CDO-1 includes 5 TAF/yr of CAP water being recharged near the top of Big Wash in the CDO watershed over the projection period. Figures 34 to 38 share a color scale.

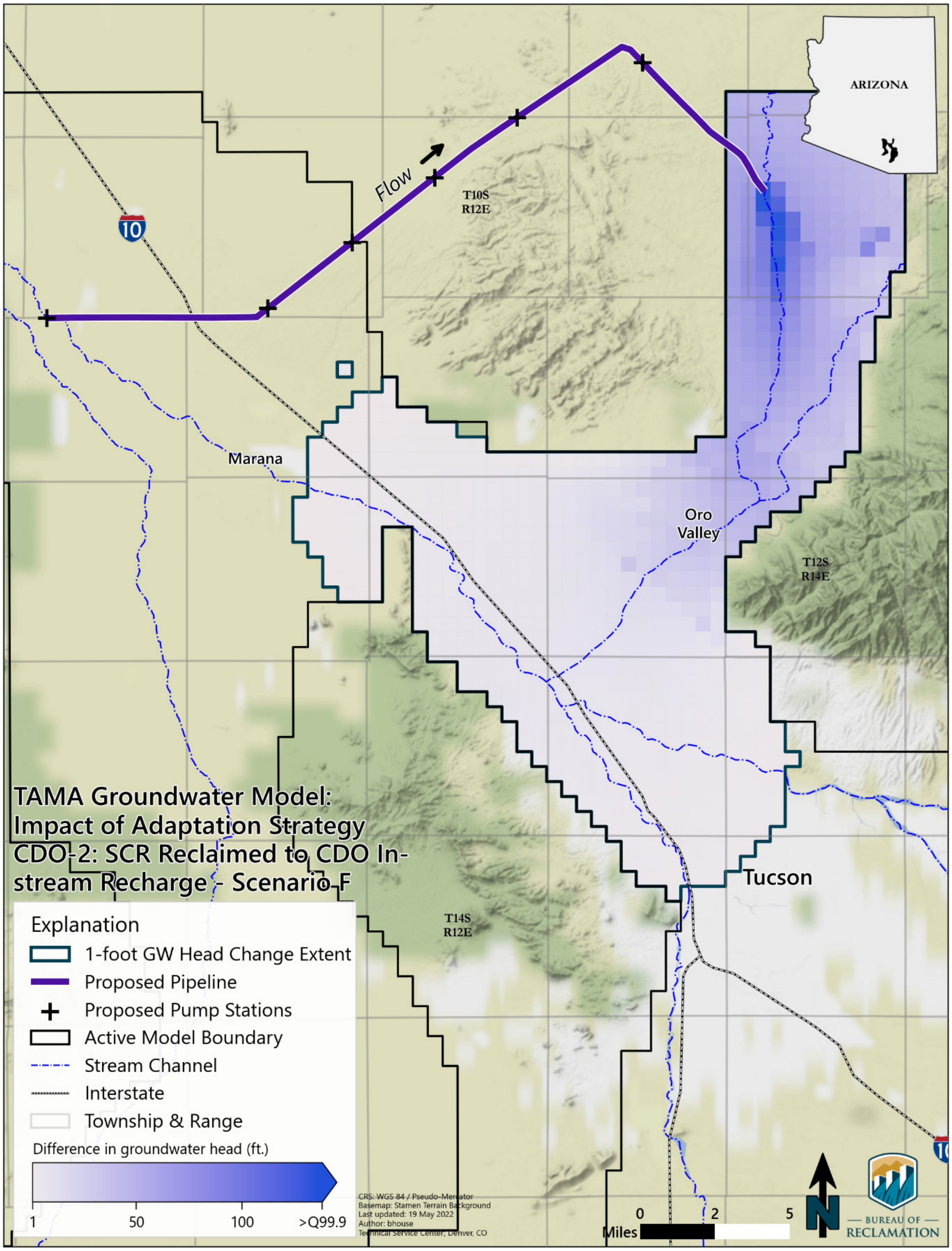

Figure 35. Difference in the simulated groundwater table for scenario F with inclusion of adaptation strategy CDO-2. CDO-2 includes 10 TAF/yr of reclaimed water diverted from the SCR being recharged near the top of Big Wash in the CDO watershed over the projection period. Figures 34 to 38 share a color scale.

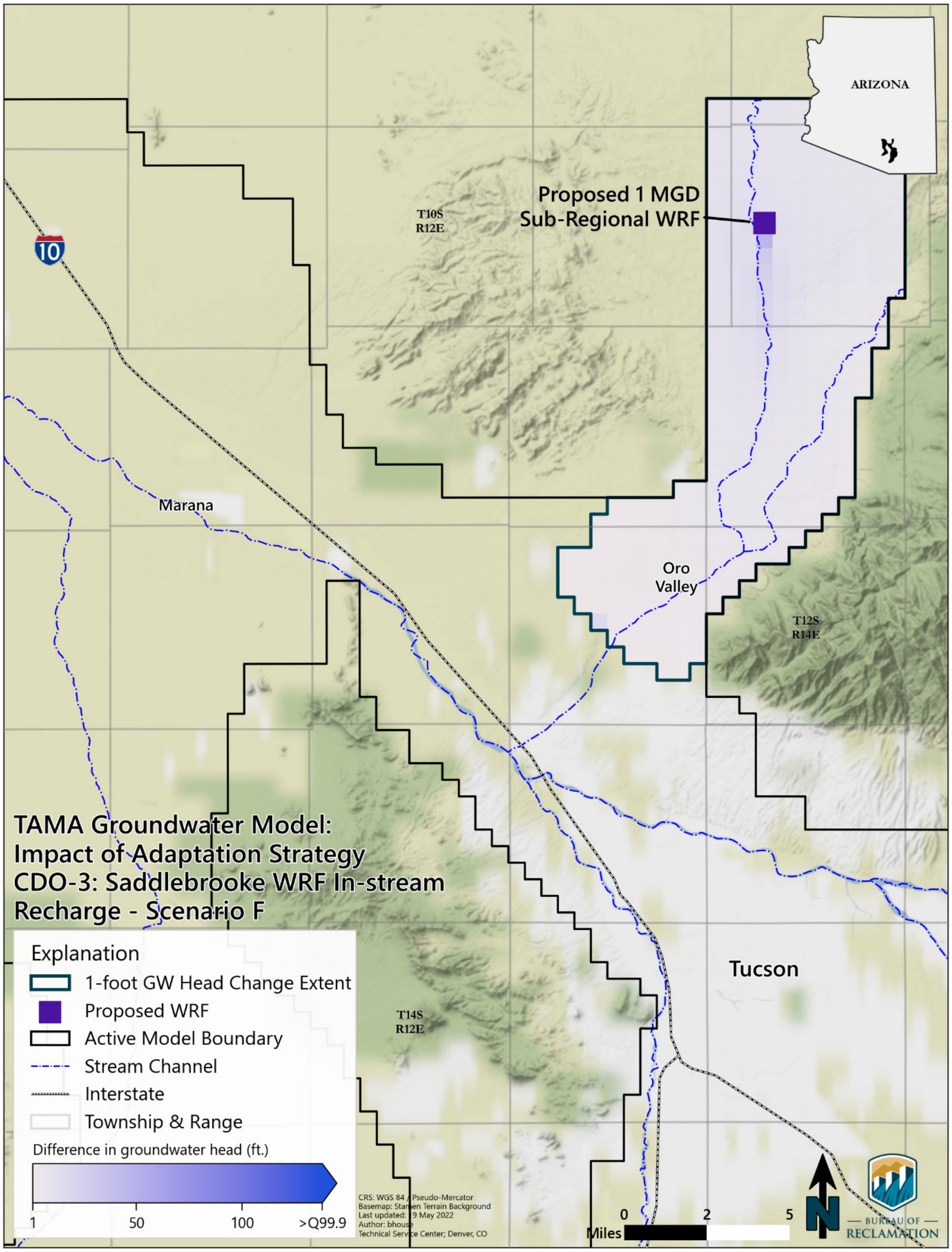

Figure 36. Difference in the simulated groundwater table for scenario F with inclusion of adaptation strategy CDO-3. CDO-3 includes 1.12 TAF/yr (1 MGD) of reclaimed water recharged near the top of Big Wash in the CDO watershed from a potential WRF over the projection period. Figures 34 to 38 share a color scale.

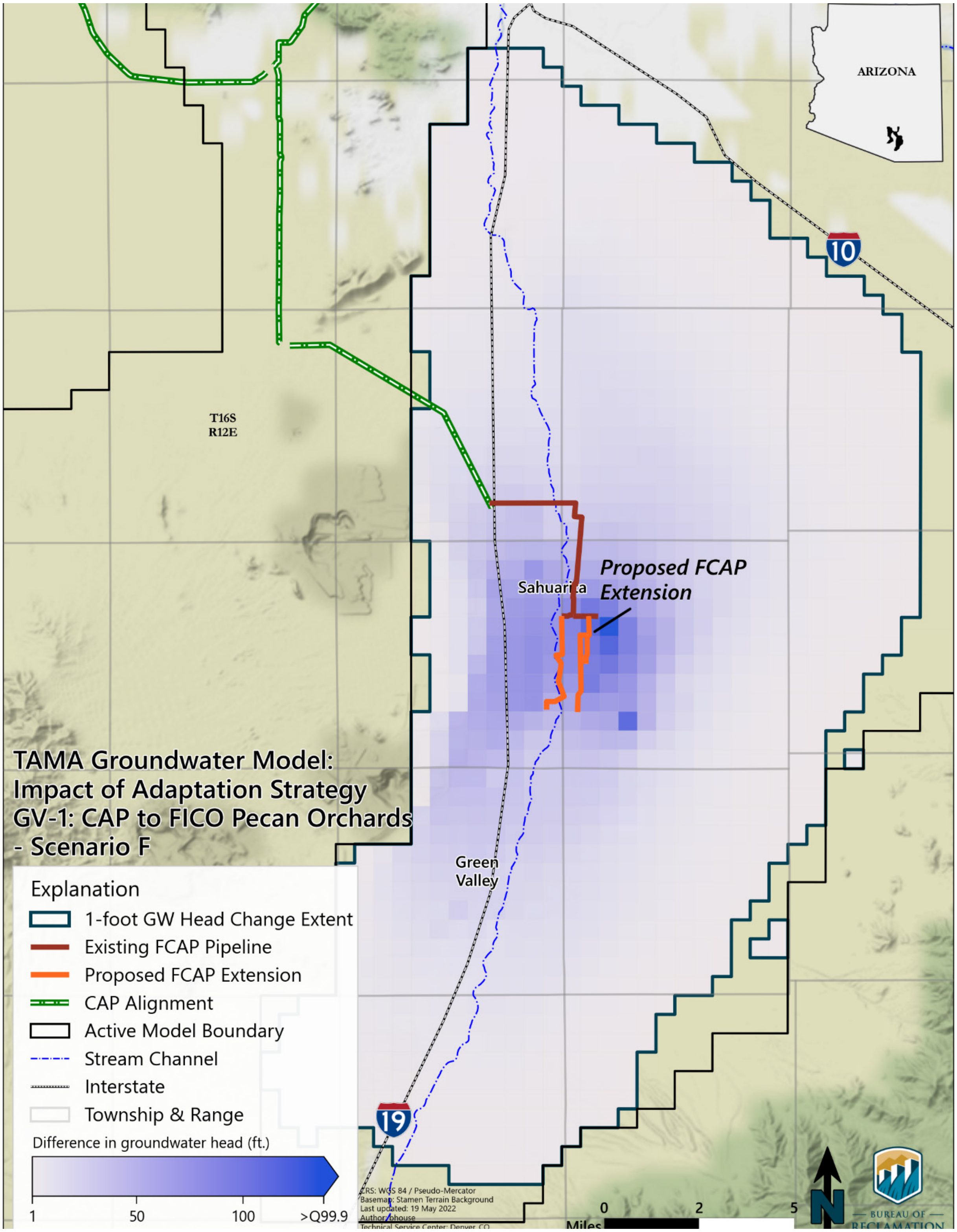

Figure 37. Difference in the simulated groundwater table for scenario F with inclusion of adaptation strategy GV-1. GV-1 includes providing CAP surface water supplies in lieu of pumping groundwater to meet irrigation demands for FICO through the extension of the FCAP pipeline. This offsets about 10 TAF/yr of pumping starting in 2027 until the end of the projection period. Figures 34 to 38 share a color scale.

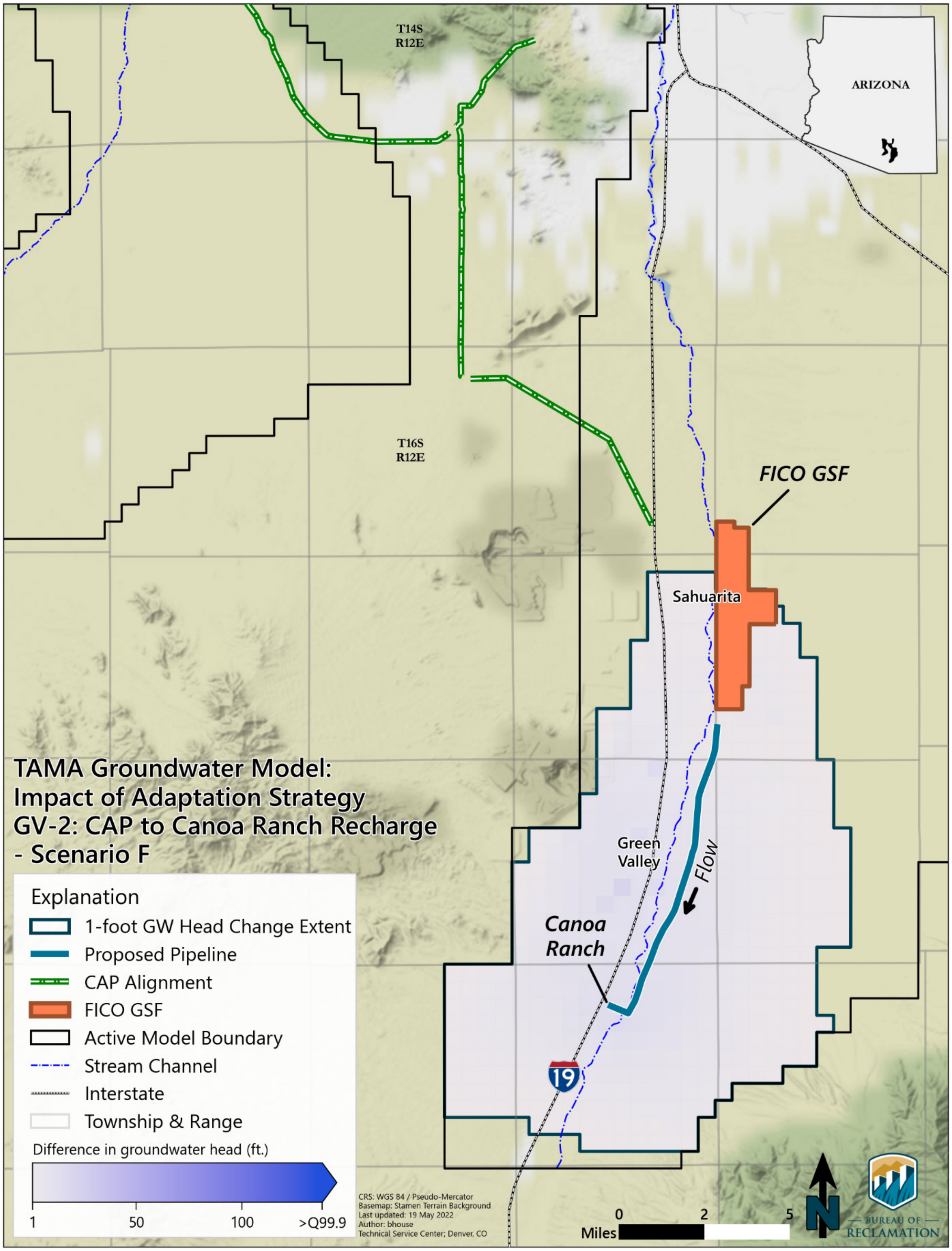

Figure 38. Difference in the simulated groundwater table for scenario F with inclusion of adaptation strategy GV-2. GV-2 includes extension of a pipeline to the Canoa Ranch. Here, 2 TAF/yr of CAP water would be recharged when capacity in the pipeline was available (i.e., not during the growing season) over the projection period. Figures 34 to 38 share a color scale.

This analysis demonstrates that the five strategies identified by the Study Partners and simulated using the TAMA Model all result in a projected increase in the groundwater table by at least a foot over large portions of the TAMA Model domain. The impact of a given strategy is proportional to the rate of additional recharge or pumping offset. As the rate of discharge to a stream channel increases, the model simulation shows that water will travel farther down the channel before infiltrating.

The hydrogeologic properties of the area where adaptation occurs also impact the results. For example, results from GV-2 (Figure 38) indicate minimal groundwater mounding near the recharge site and a 1-foot impact extent propagated farther in the north-south direction. These results are due to the relatively high horizontal hydraulic conductivity (causing the recharge to spread faster and not mound), and higher hydraulic conductivity along the SCR (allowing recharge to propagate faster along the SCR in the north-south direction; hydraulic conductivity distribution is shown in Figure 4). An economic analysis of these adaptation strategies was also conducted as part of the Basin Study. Results of the economic analysis are presented in a separate Technical Memorandum.

5. Summary and Conclusions

Infiltration of both natural and reclaimed water streamflow along stream channels and recharge at artificial recharge facilities are the major sources of inflows to the LSCR Basin groundwater system over the projection period (Table 5; Figures 21 and 22). Recharge is strongly influenced by future climate, with large differences in projected recharge across the best-case and worse-case climates (Figure 20). Cumulative inflows (recharge) under the current and best-case climates are about 1.6 MAF greater over the projection period than under the worse-case climate. Differences between the best-case and the worse-case climates result in a divergence in annual average recharge of about 40 TAF/yr over the projection period.

Recharge at artificial recharge facilities generally trends downward over the projection period due to projected reductions in CAP supplies. However, the interannual variability of natural stream channel recharge tends to drive the variability in recharge over the projection period (Figures 21 and 22).

Groundwater pumping is the predominant outflow from the LSCR Basin groundwater system over the projection period—with pumping to meet municipal demands being the greatest among the sectors (Table 6; Figures 25 and 26). Pumping is projected to either maintain a relatively constant rate (scenarios B and D, slow/compact demand growth case) or to increase to levels similar to the historical maximum pumping rate of the 1970s (scenarios C and F, rapid/outward demand growth case; Figure 23). Increases in pumping under the rapid/outward demand growth case are primarily driven by rising demands in the municipal sector (Figure 26).

Results from the TAMA Model projections suggest that under all S-D scenarios included in this Study, LSCR Basin-wide groundwater storage will increase over the projection period (Figure 27). While the S-D scenario with higher risk to water resources (F) is generally in overdraft for the final 10-years of the projection period, all other S-D scenarios are generally in surplus (Figure 27). However, while total groundwater storage within the LSCR Basin is projected to increase from current levels, model results indicate substantial declines in groundwater heads and storage in some areas of the LSCR Basin (Figure 28).

Both climate and demand growth impact groundwater supply. While the impact of lower atmospheric GHG concentrations (best-case climate [RCP 4.5]) shows some localized and broad increases in the simulated groundwater table (Figure 31), the impact of reduced demand growth (slow/compact) is often more localized (Figure 32). Impacts to groundwater resources within the Study area reflect the effects of climate conditions on both local streamflow within the LSCR Basin as well as CAP water availability within the broader Colorado River Basin. This highlights that the future of groundwater resources within the LSCR Basin depend not only on climate changes within the Study area, but also on changes for the Colorado River Basin as a whole. The water supply future of the LSCR Basin is linked to that of the Colorado River Basin through the import of Colorado River water via the CAP. By the end of the projection period, about 60% of the range of projected change in groundwater storage is due to the climate (Figure 33). The remaining 40% is due to the differences in demand growth.

Five adaptation strategies were simulated with the TAMA Model to evaluate the impact each would have on the groundwater table at the end of the projection period. Simulations were conducted as if a given adaptation strategy was implemented for the duration of the projection period (40 years). All simulations were conducted under scenario F, which reflects the S-D scenario with the higher risk to water resources for this Study. Results suggest that all five strategies are effective at increasing the simulated groundwater table by at least a foot over large portions of the Study area. In general, the greater the rate of recharge or pumping offset, the greater the benefit to groundwater table.

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Appendix A—Streamflow Bias-Correction Method

A.1 Background

Projections of streamflow at 17 streamgages within the Study area were developed by Reclamation (2021) using the Sac-SMA rainfall-runoff model. These streamflow projections were subsequently used to develop streamflow infiltration inputs to the TAMA Model for the best-case and worse-case future climate scenarios as described in the *Streamflow Infiltration* section of this Technical Memorandum. Prior to developing streamflow infiltration inputs, streamflow projections were bias-corrected to correct for systematic errors (biases) between simulated historical streamflows and the observed record. This appendix summarizes the bias-correction methodology applied to streamflow projections. A variety of bias-correction methods have been applied in previous Reclamation Basin Studies. The method described here was recommended by senior technical staff at Reclamation's Technical Service Center. There are many similarities between this method and other statistically-based bias-correction methods (e.g., see Hamlet et. al. [2010] on statistical bias-correction).

A.2 Description of Methodology

The bias-correction method applied to projected streamflows for this Study is based on the relationships between simulated streamflows from the Sac-SMA model when forced with historical or future climate conditions and the observed streamflow record. The approach uses the cumulative probability distribution functions (CDF) of mean monthly streamflow (by month) from: the observed streamgage record (blue line in Figure A-1), the Sac-SMA historic simulation (green dashed line in Figure A-1), and the Sac-SMA projection simulation (red dashed line in Figure A-1) to produce a transformed version of the observed record (black line in Figure A-1). The resulting transformed version of the observational record reflects the projected change in CDF of monthly streamflows between the Sac-SMA historical and projection simulations.

Differences between the CDFs of mean monthly observed streamflow and Sac-SMA historic simulated streamflow (blue line and green dashed line in Figure A.1) reflect biases in the Sac-SMA model, as well as biases in each downscaled GCM. (For more information on how model bias was addressed during development of the streamflow projections see section *2.2.2.1. Bias Correction* in Reclamation [2021]). Differences between the CDFs of mean monthly Sac-SMA historic and projection simulations (green and red dashed lines) reflect the impacts of changes in climate on streamflow in the Study area. The bias-correction method applied here relies on both sources of information to develop a CDF of bias-corrected future streamflows for use in this Study. The method is applied on a streamgage-by-streamgage basis.

The relationship between the simulated historic and projected CDFs (the difference between the green and red dashed lines in Figure A-1) is imposed on the observed record through exceedance probability (quantile) mapping. This approach preserves the observed streamflow values but transforms the probability of a particular flow occurring during the projection period. This transformation represents the simulated change in streamflows between the historic and projected conditions. The sequencing of flows from the Sac-SMA projections is preserved through the projection period. The sequencing in the Sac-SMA projections is a product of the stochastic weather generator (Reclamation, 2021).

This method assumes that the CDF of monthly streamflow from the Sac-SMA historic simulation should be similar to that from the observed record. Due to systematic errors in both the Sac-SMA model configuration and the GCMs used force it, residuals between the observed and simulated streamflows are present. For example, in Figure A.1 the Sac-SMA historical CDF (green dashed line) is below the observed CDF (blue line) for streamflows less than approximately 10^1 cfs and above it for streamflows greater than 10^1 cfs. This would suggest that, for this particular month and streamgage, the bias in the GCMs and Sac-SMA result in overestimating streamflow at lower flow rates (<10^1 cfs) and underestimating streamflow at higher flow rates (>10^1 cfs).

A.3 Implementation of Methodology

Bias-correction of mean monthly streamflow projections is implemented using a Python script. The script applied the bias-correction method independently for each month of the year (i.e., Jan, Feb, …, Nov, Dec), Sac-SMA streamgage, and weather generator realization. Linear interpolation between discrete values within a given CDF is applied during the bias-correction process. After constructing CDFs for the three input datasets, execution of the script follows the steps below (and is depicted in Figure A.1):

1. Obtain a mean monthly streamflow from the Sac-SMA projection simulation (e.g., 15 cfs in January 2055).
2. Calculate the exceedance probability of the projected flow occurring in the Sac-SMA historic simulation period (e.g., 0.7).
3. Calculate the streamflow with equal exceedance probability from the observed streamgage record CDF (e.g., 35 cfs).

The mean monthly streamflow from the Sac-SMA projection simulation is then replaced with the bias-corrected value for the given month (e.g., for January 2055, 15 cfs is replaced with 35 cfs). For this example, the CDF of the bias-corrected flows (i.e., transformed version of the observed record) is shown as the black line in Figure A.1. The resulting difference between the observed record and bias-corrected CDFs (blue and black lines in Figure A.1) reflect the differences between the Sac-SMA historic and projection simulation CDFs (green and red dashed lines in Figure A.1). In this example, these differences include an increased probability of no and lower streamflows. This is expected since the bias-correction method imposes the simulated change in projected streamflow upon the observed record.

This bias-correction process does not alter the temporal sequencing of low and high flows from the Sac-SMA projection simulation. The sequencing of flows is predominantly a result of precipitation from the weather generator employed by Reclamation (2021). The weather generator ingests information on temporal sequencing of precipitation from downscaled GCMs. The resulting total annual TAMA Model-wide groundwater recharge from the bias-corrected streamflows for the two future climate scenarios are shown in Figures 11 and 12. Comparison of the projections of groundwater recharge from infiltration of bias-corrected streamflows to historic simulated rates from ADWR (2020b) indicates reasonable agreement in both sequencing and magnitude of annual totals.

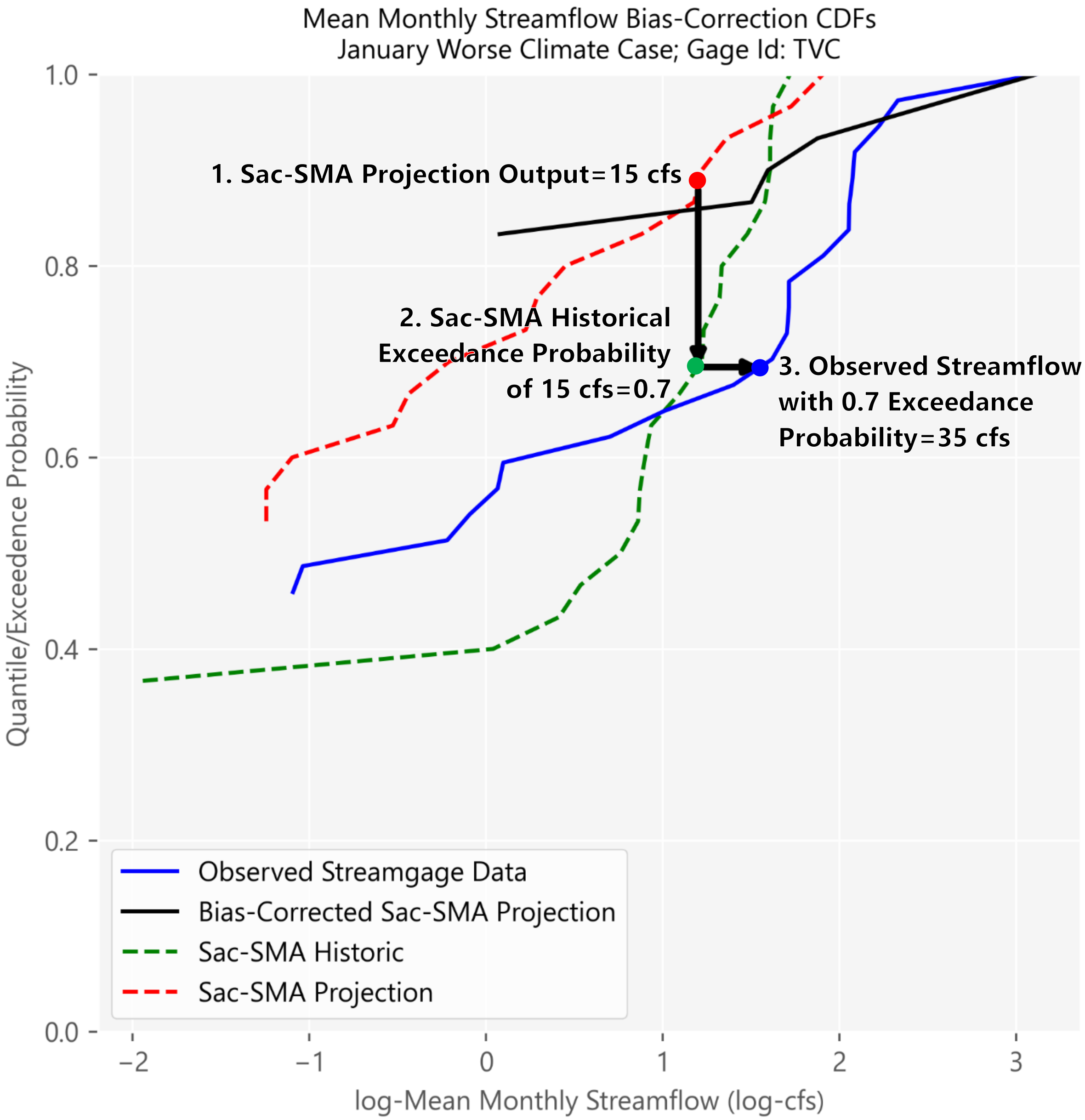

Figure A-1. Illustrative CDFs for mean monthly streamflow bias-correction process. Data are from January of the worse-case climate scenario for Sac-SMA gage TVC. An example of the bias-correction process is depicted for a projected mean monthly streamflow of 15 cfs ($10^{1.18}$ log-cfs).

A.4 Assumptions and Limitations

An assumption of this bias-correction method is that the maximum mean monthly flow during the projection period does not exceed maximum mean monthly flow in the observed record. This assumption eliminates the potential for unrealistically large future streamflows from being simulated. However, this assumption could have the potential to mute projections of greater than historic streamflows. The impact of this is partially mitigated as streamflows are aggregated to mean monthly rates—and ultimately to a total annual groundwater recharge rate.

The method also assumes that the impact of historical model biases is transferable to the future period. Information on the downscaled GCM and Sac-SMA model biases is contained within the difference between the CDFs of mean monthly observed streamflow and Sac-SMA historic simulated streamflow. This method assumes that the impacts of this bias are also applicable to the projection period. The impact of this assumption is likely to be greater if the projected model forcings deviate significantly from historic forcings.

This method is also sensitive to the breadth of data contained in the observed record. The method inherently assumes that any discrepancy between the observed and Sac-SMA historic simulation is due to model bias. It is possible that the streamgage record could have a limited number of observations that do not represent the actual range of possible streamflows. This sensitivity was mitigated in this Study through expansion of the observed record at select streamgages based on historic simulated groundwater recharge from ADWR (2020b).

This bias-correction method should undergo additional evaluation if it were to be applied to data with a shorter timestep (e.g., daily). For this Study, estimates of total annual streamflow infiltration were required. Figures 11 and 12 indicate that reasonable recharge sequencing and magnitudes were achieved. Figure 14 also shows that the projected changes in streamflow (and therefore infiltration) under each future climate scenario concluded by Reclamation (2021) are represented in these results. However, working with data on a shorter timestep is likely to present additional challenges that would require further evaluation.

Appendix B—Groundwater Model Results: Simulated Change in Head Maps

Detailed, full-page maps of the simulated change in groundwater head by model cell over the projection period (2020-2060) for each Basin Study S-D scenario (A-F) are included here for ease of review. These results are identical to those presented in Figure 28 of the main body of this Technical Memorandum.

Figure B-1. Change in groundwater table by groundwater model cell over the Study projection period (2020-2060) for scenario A (current climate, medium/official demand growth).

Figure B-2. Change in groundwater table by groundwater model cell over the Study projection period (2020-2060) for scenario B (best-case climate, slow/compact demand growth).

Figure B-3. Change in groundwater table by groundwater model cell over the Study projection period (2020-2060) for scenario C (best-case climate, rapid/outward demand growth).

Figure B-4. Change in groundwater table by groundwater model cell over the Study projection period (2020-2060) for scenario D (worse-case climate, slow/compact demand growth).

Figure B-5. Change in groundwater table by groundwater model cell over the Study projection period (2020-2060) for scenario E (worse-case climate, medium / official demand growth).

Figure B-6. Change in groundwater table by groundwater model cell over the Study projection period (2020-2060) for scenario F (worse-case climate, rapid/outward demand growth).

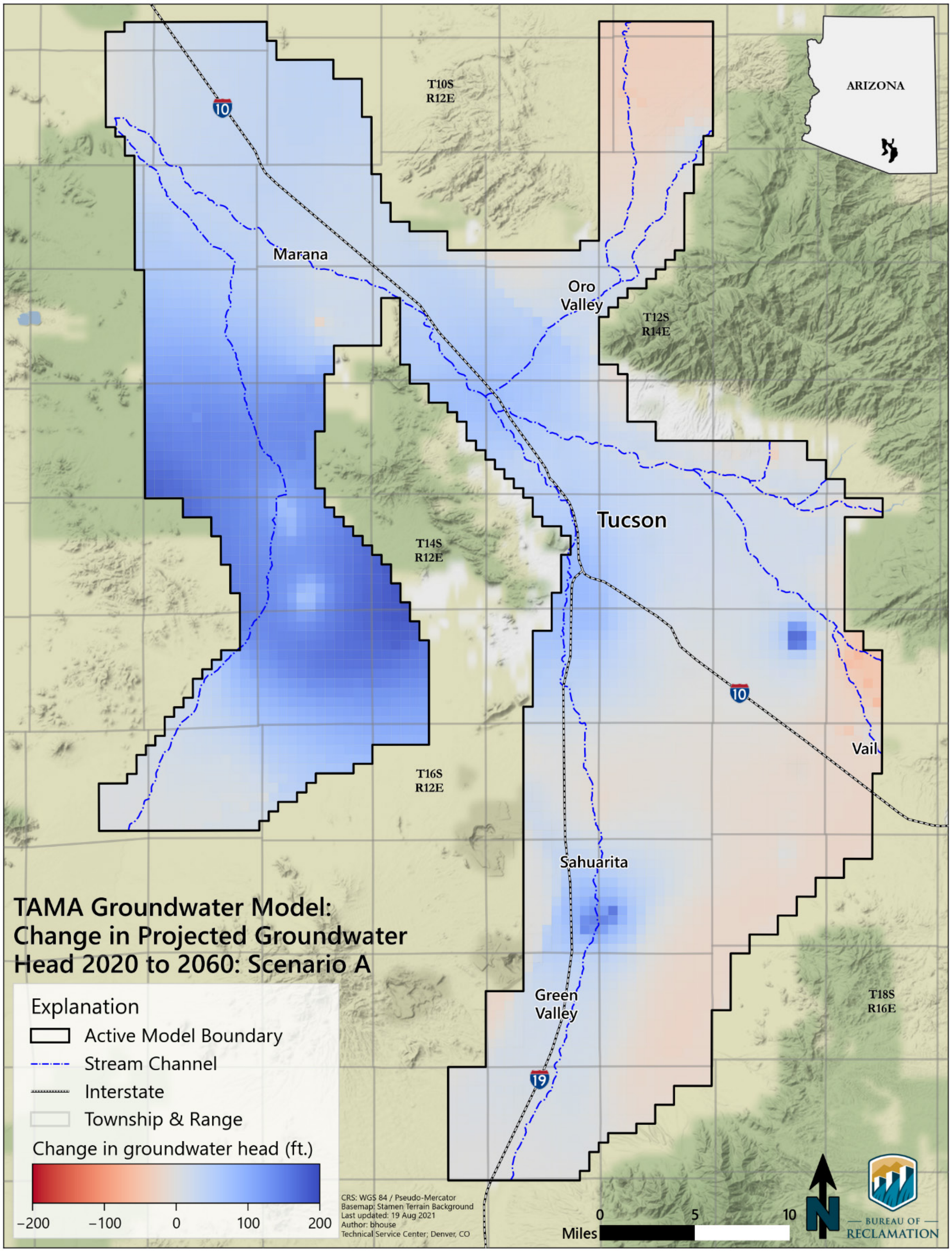

Figure B-1. Change in groundwater table by groundwater model cell over the Study projection period (2020-2060) for scenario A (current climate, medium/official demand growth).

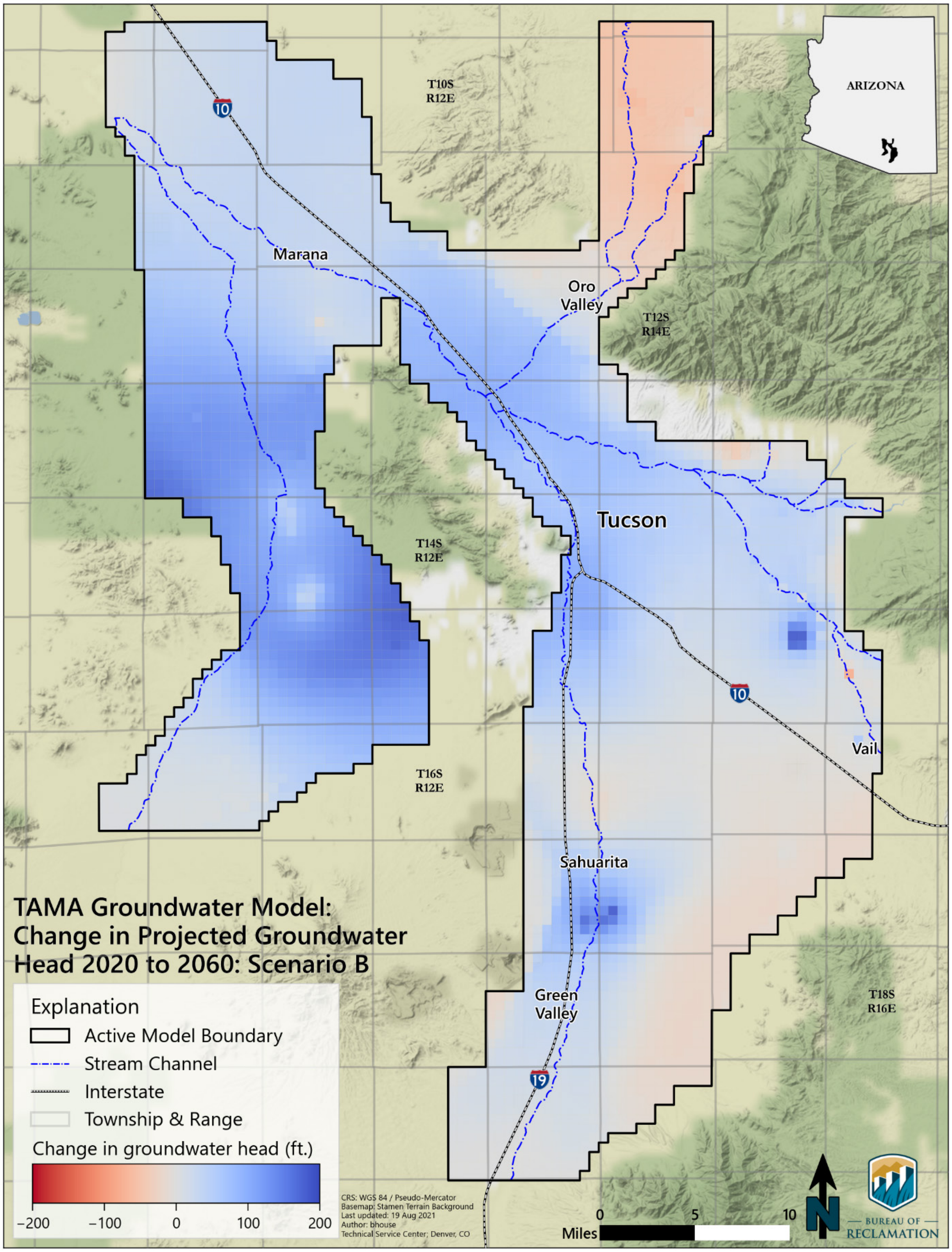

Figure B-2. Change in groundwater table by groundwater model cell over the Study projection period (2020-2060) for scenario B (best-case climate, slow/compact demand growth).

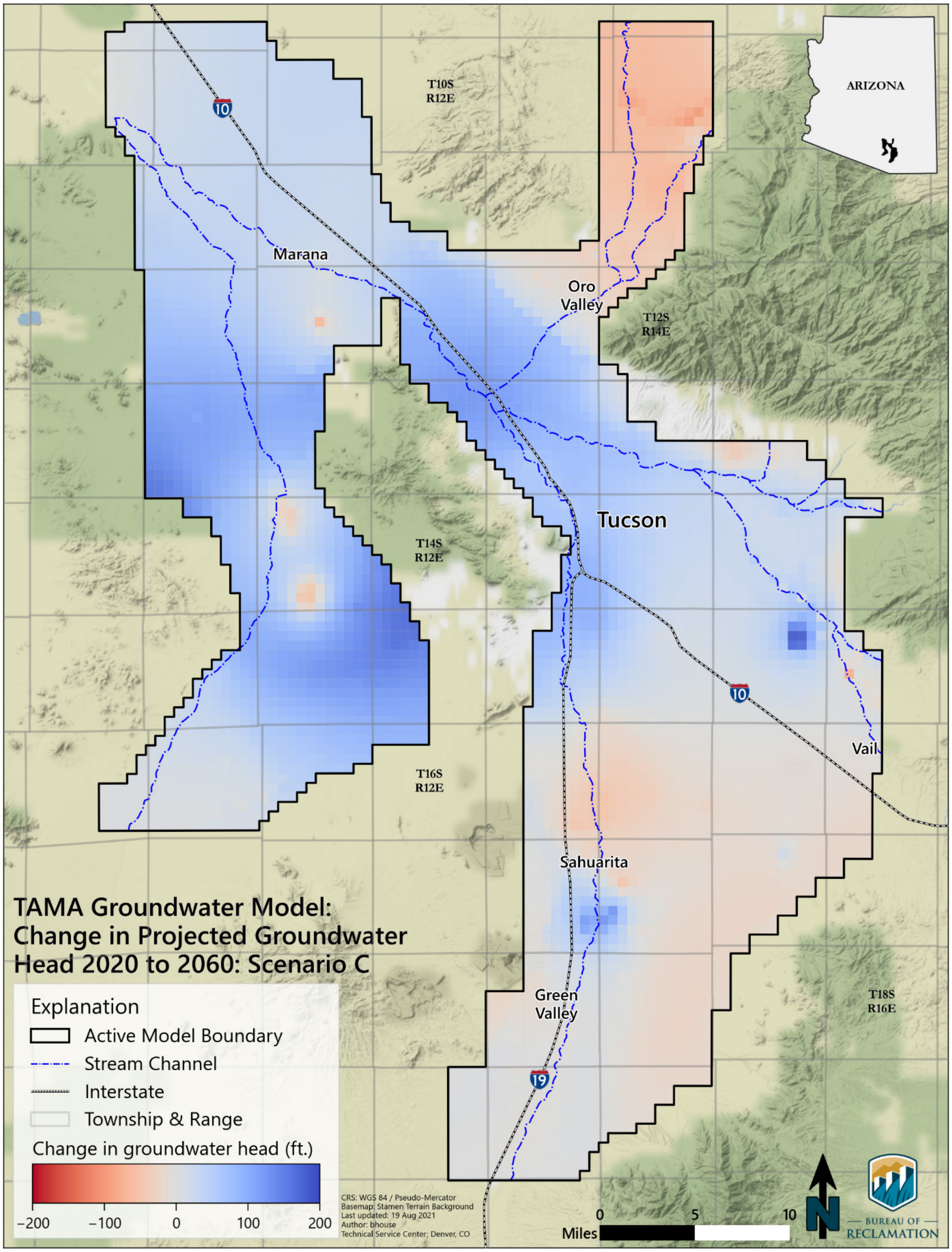

Figure B-3. Change in groundwater table by groundwater model cell over the Study projection period (2020-2060) for scenario C (best-case climate, rapid/outward demand growth).

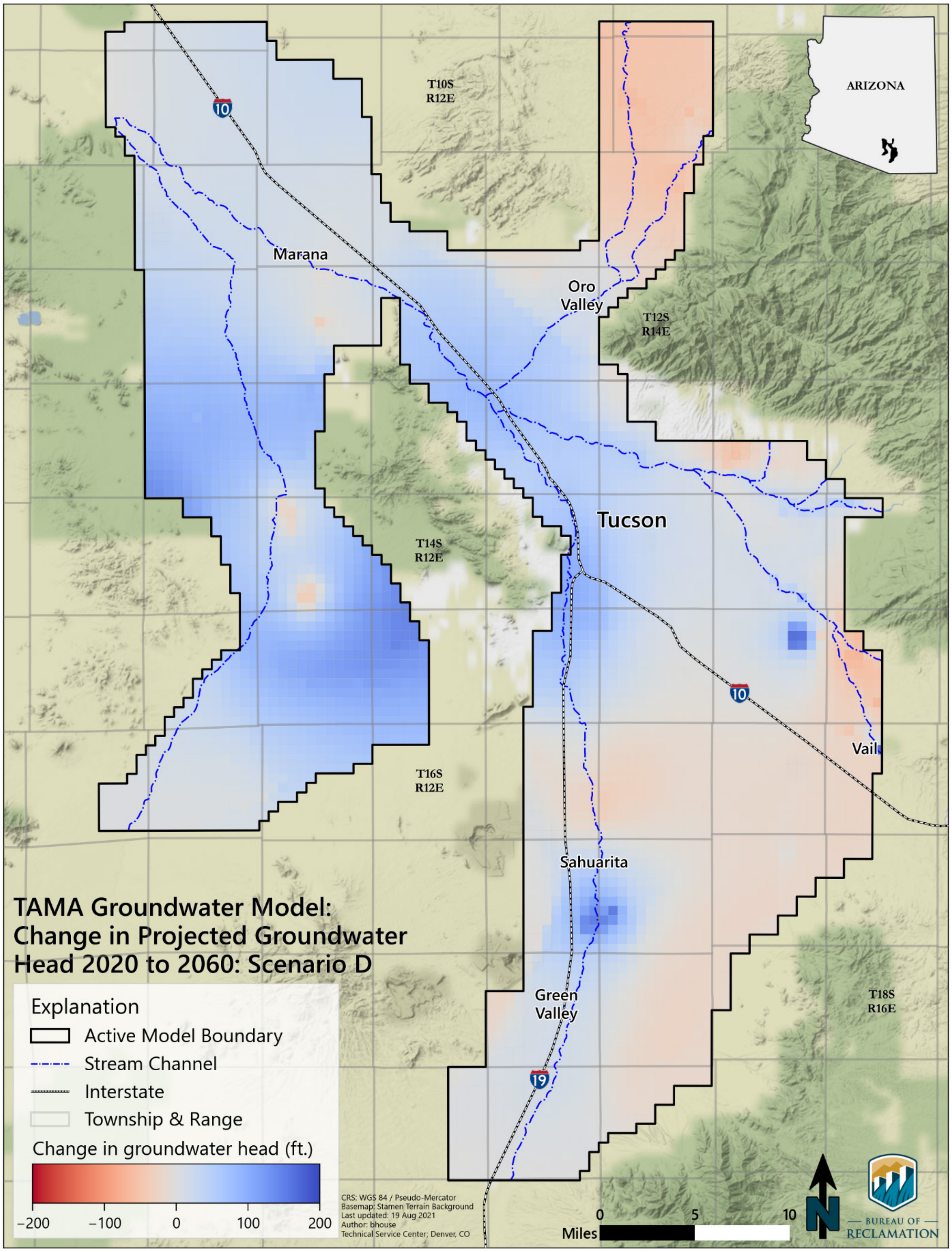

Figure B-4. Change in groundwater table by groundwater model cell over the Study projection period (2020-2060) for scenario D (worse-case climate, slow/compact demand growth).

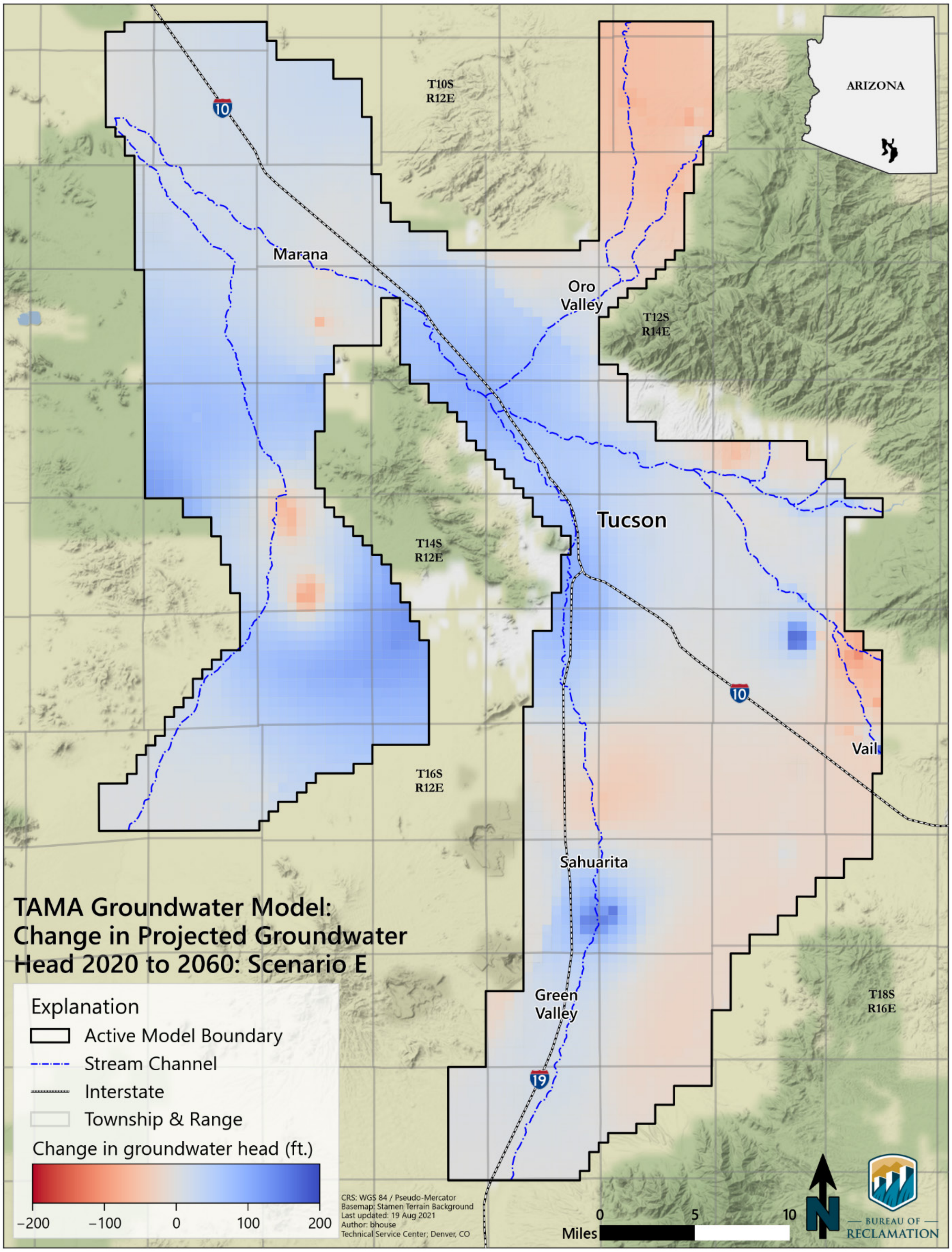

Figure B-5. Change in groundwater table by groundwater model cell over the Study projection period (2020-2060) for scenario E (worse-case climate, medium/official demand growth).

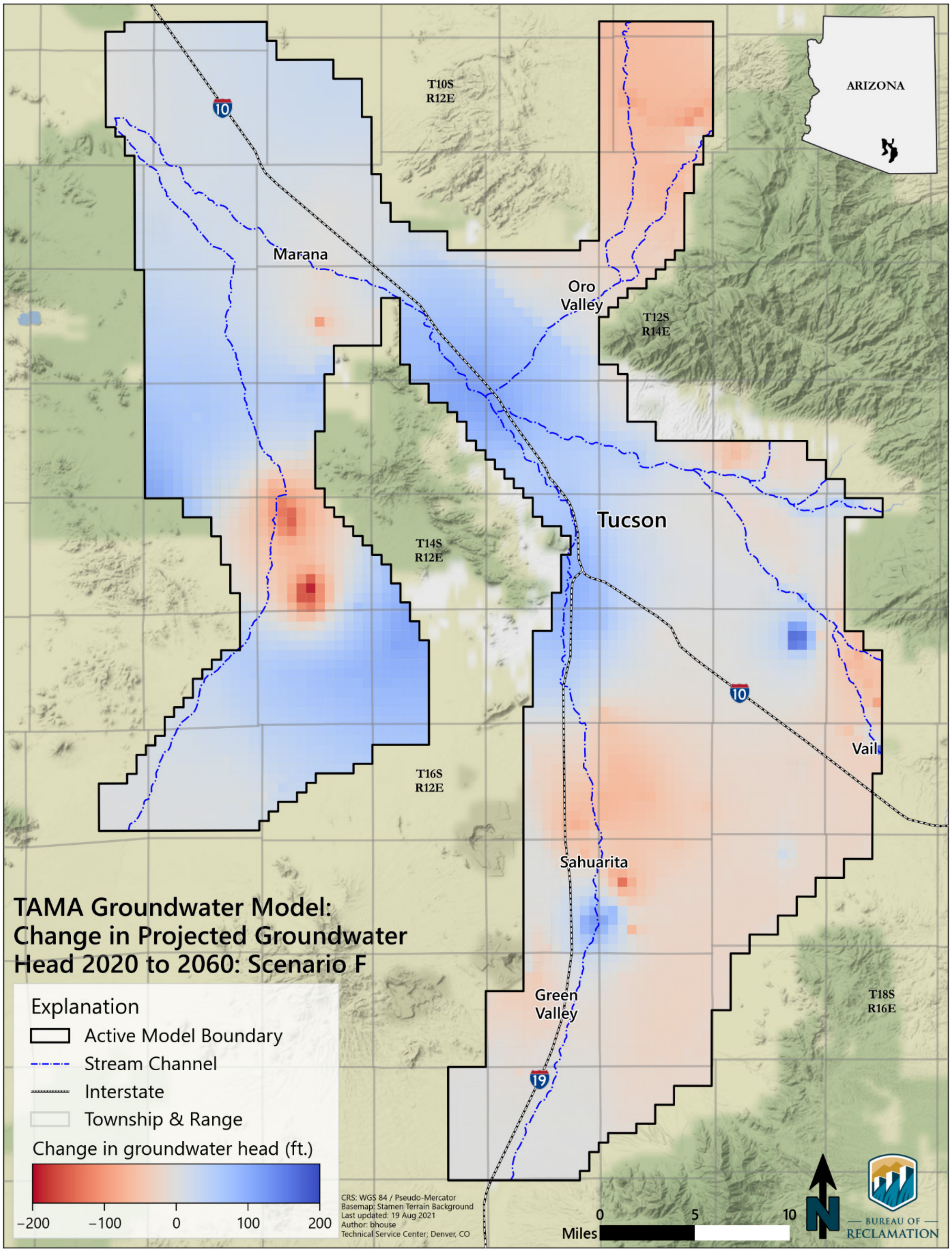

Figure B-6. Change in groundwater table by groundwater model cell over the Study projection period (2020-2060) for scenario F (worse-case climate, rapid/outward demand growth).