ARIZONA TRI-UNIVERSITY

RECHARGE AND WATER RELIABILITY PROJECT REPORT

Arizona State University

The University of Arizona

Northern Arizona University

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FOREWORD

The origins of the Arizona Tri-University Recharge (ATUR) and Water Reliability Project lie with a program of the Arizona Board of Regents (ABOR), which oversees the three Arizona universities. ABOR occasionally provides direct grants of money from the Technology & Research Initiative Fund (TRIF), which is a sales tax that is paid to the state of Arizona to support education and innovation. Although the majority of these funds go to K-12 education, a portion goes to the universities. In this case, ABOR designed a grant program based on the needs of state agencies for solutions to particular problems. Among the problems that were named by the Arizona Department of Water Resources (ADWR) was increasing concern about the reliability of water supplies across the state, and the associated need to explore potential new sources of water. The desired solution was to find ways to capture water that would otherwise have evaporated into the atmosphere, and to identify methods to recharge groundwater supplies. ABOR required that the three universities (Arizona State University, Northern Arizona University, and the University of Arizona) work together to develop proposals, and the ATUR proposal was selected by ADWR. The primary research questions are 1) where can water be captured across the state in a manner that does not impact existing water rights? and 2) how and where could this water be recharged?

The initial Principal Investigator for this project was Dr. Thomas Meixner, who at the time was the chairman of the Hydrology and Atmospheric Science Department at the University of Arizona (UA). Tom was a universally well-liked professor, a talented researcher, and a very collaborative person who loved working on applied projects. Tom's life was cut short the day after he initially presented this project proposal to ADWR. The ATUR team owes him a debt of gratitude for his initial ideas and teambuilding as well as the substantial contributions he made to water research, community initiatives, and collaboration in Southern Arizona; those of us who knew him still mourn his loss.

Because the motivation for this work is directly tied to water management objectives and challenges across the state, background information is provided below for context.

Introduction to Water Management in Arizona

The state of Arizona is the sixth largest state in the US, covering almost 114,000 square miles. Although much of the state is considered arid to semi-arid, some watersheds in the state average over 20 inches of annual precipitation. Although Indigenous people lived in harmony with the available water resources for millennia and developed sophisticated irrigation and farming systems, the need for increasing access to water in the Southwest has been a constant theme at least since the John Wesley Powell expedition explored the Grand Canyon in 1869. Statesmen and politicians have promoted ways to enhance Arizona's water supplies through deliveries from the Gila, Salt and Verde Rivers, and the Colorado River since the beginning of the 20th century, ultimately leading to the completion of the Salt River Project, serving the Phoenix area, and the Central Arizona Project (CAP), which serves three counties (Maricopa County, Pinal County, Pima County) in the center of the state.

Prior to the development of the CAP, most water users without direct access to the Colorado, Salt or Verde Rivers were dependent on groundwater wells. The rate at which groundwater was withdrawn exceeded the natural recharge of many groundwater aquifers since at least the 1940s, when turbine pumps were first installed to serve large-scale agriculture. By the mid-1970s multiple aquifers across the state were experiencing increasing depletion, leading to the development of the 1980 Groundwater Management Act (GMA). The GMA focused on stabilizing Arizona's economy and ending groundwater overdraft in the central urbanized areas of the state, establishing four initial Active Management Areas (AMAs) in Prescott, Phoenix, Pinal and Tucson. At the same time, two initial Irrigation Non-Expansion Areas (INA's: Harquahala and Joseph City) were named in more rural basins facing less dramatic depletions. Since 1980, there have been additional AMAs and INAs established, but the majority of the state still lies outside of either form of groundwater management area (ADWR AMA overview map). Outside of the AMAs, groundwater depletion continues and there are limited tools to regulate groundwater use by industries and communities.

The primary regulatory tools of the GMA are: 1) establishment of grandfathered rights to groundwater for existing agricultural, industrial and municipal users, with strong limits on all new large uses of water; 2) mandatory conservation requirements for all large groundwater users within AMAs; and 3) the Assured and adequate Water Supply (AWS) program, which requires new subdivisions, and/or their associated municipal water providers, to provide proof of a 100-year supply of renewable water at the time of development. In the case of municipal water providers, their designation of AWS has to be renewed on a regular basis to ensure ongoing availability of supplies. This third requirement is the major driver of the use of CAP and municipal effluent in lieu of groundwater within Arizona's AMAs. Outside of the AMAs, some counties, cities and towns have voluntarily adopted Adequate Water Supply requirements to support water management (e.g., Cochise and Yuma Counties, Towns of Clarkdale, Camp Verde, Patagonia and many have designations of Water Adequacy, e.g. Flagstaff). Though there are many legal complexities and some exemptions associated with these regulatory tools, the GMA's primary objectives have generally been upheld over the last 45 years. That said, much of the success of the GMA in reducing overdraft is dependent on Colorado River supplies, which are the subject of increasing concern.

After a century of litigation and legislative agreements, collectively called the "Law of the River," Arizona's allocation of CAP water is the lowest priority on a river that is already notoriously over-allocated due to incorrect historical conclusions about average flows. In addition, climate change impacts are reducing the flow in the river over time, in large part due to increasing temperatures affecting snowpack and surface runoff. Another component of the diminished flow of the Colorado River is reduced groundwater-supported base flow associated with over-pumping the aquifers in the basin. The combination of over-allocation and reduction in average flows have resulted in the major Colorado River reservoirs, lakes Powell and Mead, being at the lowest levels since the reservoirs were initially filled. This means that Arizona is no longer able to take its full allocation of CAP water, and deliveries within the state have been significantly curtailed. There is no obvious relief in sight, and negotiations over the management of the river are still ongoing as of this writing. Even in the event of a few good water years, which could at least partially refill the reservoirs, it is clear that the Colorado River will not be the fully reliable source of water supplies it was once hoped to be.

Meanwhile, for the more than three-fifths of the state that has no access to Colorado River water, a combination of climate change and other factors are significantly impacting natural recharge processes. Soil moisture is decreasing, groundwater levels are declining, rangeland and riparian (stream-related) environments are experiencing degradation, and forested areas have been burning at unprecedented rates. In addition, the lack of water use management and regulation in these areas means that they have been targeted by large water users, including large-scale agricultural producers, and groundwater depletions are accelerating, leading to litigation as well as the recent establishment of several new management areas.

This project employed a multi-pronged approach to identify opportunities to capture rain, snow, and urban runoff that is not currently appropriated by surface water rights holders and would otherwise be available and finding places and mechanisms for recharging that water. Between January 2023 and June 2026, approximately 40 faculty members, graduate and undergraduate students, and postdoctoral scholars contributed to this effort. The project provided a valuable opportunity for these participants to work as an interdisciplinary team to address complex scientific challenges in a real-world context. We are grateful to ABOR and ADWR for their support and for making this work possible.

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This report was developed in a highly collaborative, interdisciplinary fashion; all team members were provided with opportunities to engage in and contribute to all activities. For this reason, we provide a list of "Primary Contributors" for each Key Message in case there are questions, but the work and ideas of all team members is represented in each chapter.

We are grateful to Melina Lew for her assistance with graphics and report layout.

EXECUTIVE SUMMARY

Introduction

The Arizona Tri-University Recharge and Water Reliability (ATUR) Project was initiated, designed, and implemented in response to interests of the Arizona Department of Water Resources (ADWR), and funded by the Arizona Board of Regents (ABOR). The main goal of the project was to investigate opportunities for capture and recharge of waters across the state of Arizona in a manner that is consistent with existing water rights, laws and policies. The ATUR project is focused on ways to harvest and recharge waters that would otherwise be lost via evaporation, transpiration, and/or snow sublimation, as well as additional runoff generated through urban development or impacts from wildfires. This report provides decision support but does not include recommendations regarding specific locations or techniques; it should be viewed as a scientific foundation that can support land and water resource management across the state at multiple scales.

Project Approach

The Arizona Tri-University Recharge and Water Reliability (ATUR) project was initiated to develop foundational, hydrological characterizations of 1) how components of the natural hydrologic cycle water balance (i.e. precipitation, evapotranspiration, runoff, and recharge) are partitioned across the state, and 2) how management strategies can influence water balance components to support broader goals of water capture and recharge. The ATUR project involved multiple researchers from across Arizona's state universities (University of Arizona, Arizona State University, and Northern Arizona University), using a combination of investigative techniques that include hydrological and climate modeling, remote sensing, machine learning (ML) and GIS-based approaches. Notable key messages are summarized in this Executive Summary, and supporting material for these key messages is integrated throughout the full report. We have provided links to all of the original data that we generated, as well as to an array of additional products: StoryMaps, annotated literature reviews, peer reviewed publications, etc.

Many opportunities for enhanced capture of rainfall/snowmelt/urban runoff and subsequent recharge were identified for Arizona's diverse landscape types, and we have included considerations of their potential limitations and environmental impacts (see Appendix F: Recharge Opportunities Matrix). This matrix should not be viewed as a complete analysis of the feasibility of each option, but rather a synopsis of strategies that should be further considered in the context of legal, physical, and environmental conditions in particular places. Some of these management options (e.g. flooding potential and forest thinning) were included in a detailed analysis of surface and subsurface conditions statewide, and evaluated using a GIS-based approach, to characterize their suitability for enhancing groundwater recharge (see Statewide Suitability Analyses).

In addition to technical investigations, the study has employed a robust stakeholder engagement process that included regular meetings with ADWR, the project's Technical Advisory Committee (see Appendix H), as well as stakeholders representing a diversity of perspectives and interests that include local, state, Tribal, and federal land and water managers, scientists and NGOs to ensure relevance and utility of project deliverables to ongoing work throughout the state and to support identification of potential future project partners. In all, the team conducted nearly 90 meetings and workshops with more than 80 organizations and individuals. In most cases, these entities and individuals engaged with us multiple times.

Summary of Key Findings

In order to answer the questions that were provided by ADWR, we need to 1) understand the current hydrologic system and existing water balances for each basin; 2) identify where evapotranspiration is greatest since that is the largest potential new source of water; 3) find methods and locations to reduce ET and increase recharge both now and in the future; and 4) understand long-term changes in climate conditions.

The ATUR project has developed information about past, current, and future natural hydrologic cycle water balances, and strategies to enhance capture and recharge in Arizona's groundwater basins. A high-level overview of the findings is described below. A comprehensive summary of key findings from this research, along with links to literature reviews, data, tools, and models are described throughout the full report. Although we have relied on material in past reports to some degree, this project has generated new sources of information that were not previously available. For example, we developed and tested new data from the National Water Model as well as more sophisticated regional models, new satellite and remote sensing products, and deployed new tools such as machine learning and big data analysis. The latest data from 14 global climate change models were tested and bias-corrected for use in our region to generate future temperature and precipitation inputs to the individual basin water balances. Statewide long-term projections were developed using an ensemble of climate and land surface model outputs for precipitation, evaporation, transpiration, recharge and runoff. Capture and recharge suitability analyses included remote sensing, geophysical data, GIS analysis, machine learning, etc.

Statewide Water Supply Summary

Despite being known as an arid state, Arizona's lands exhibit sharp differences in landscape and climate. For example, elevation ranges from 21 meters (70 feet) above mean sea level (AMSL) near Yuma to 3,851 meters (12,633 feet) AMSL in the San Francisco peaks (USGS National Map). Mean annual rainfall across the state ranges from 63 to 1,128 mm (2.5 to 44.4 inches) (Moiz, 2025). The underlying geology, which is critical to recharge considerations, varies dramatically between the Basin and Range Province in the southern portion of the state and the Colorado Plateau in the northern part.

Our investigations of the natural hydrologic cycle across Arizona reinforce prior work estimating that over 95% of the annual precipitation that falls across the state is lost to evapotranspiration (ET). There are also areas of the state where our simulations of the natural water balance, excluding irrigation fluxes, suggest that ET exceeds precipitation, indicating a net water loss. See **Key Messages (KM)** 2.1 and 2.2.

Natural recharge peaks in early spring due to snowmelt in mountainous areas (**KM** 2.4) and occurs primarily at higher elevations, where annual precipitation exceeds 500 mm (20 inches) and surface and subsurface conditions—such as karst (limestone-based) geology and the presence of faults and fractures—are favorable for groundwater recharge. ATUR researchers have further concluded that less than 3% of annual precipitation statewide is converted to recharge (**KM** 2.3). However, on more local scales, natural recharge can vary from less than 1% in basins in southwestern Arizona to over 10% in basins along the Mogollon Rim (**KM** 2.3).

Our models further revealed that annual total precipitation is not the only factor driving recharge, but that intensity of distinct precipitation events is also a key driver, particularly during the North American Monsoon in the summer. Specifically, stronger storms (with higher precipitation intensity) lead to reduced ET and enhanced percolation, allowing more water to penetrate the root-zone and thus recharge groundwater. However, there is an optimum range of precipitation intensity for recharge because recharge can be limited if too much of the precipitation becomes surface runoff (**KM** 2.5).

Streams and rivers in Arizona are important water sources for both communities and riparian ecosystems. Results from the ATUR project show that groundwater flowing into streams, known as base flow, provides about 32% of total streamflow statewide, although this contribution varies widely across Arizona (**KM** 2.6). Base flow is generally higher in mountainous areas and lower in regions dominated by ephemeral washes that flow only after rainfall. Tracking changes in base flow over time helps water managers understand how climate variability influences groundwater availability, since base flow reflects local and regional groundwater conditions.

Arizona is experiencing declines in groundwater levels statewide. Recently, the largest declines have been in areas of the state outside AMAs that are not regulated under the GMA (it is noteworthy that several new AMAs and INAs have been created over the last few years). ATUR's model-based estimates indicate that Arizona's terrestrial water storage (TWS, which is comprised of both groundwater and surface water storage) has declined from 2000–2020 at a rate consistent with GRACE satellite observations of changes in TWS (**KM** 2.7). Our investigations attribute the loss of storage mainly to climate-related changes in recent decades, particularly warming-induced increases in evaporative demand. Anthropogenic changes in water deliveries and groundwater pumpage also affect volumes of terrestrial water storage.

In addition to historical and current hydrologic fluxes and their impact on Arizona's groundwater supplies, the future impacts of climate change on these fluxes have been investigated by our team using global climate models that have been bias corrected for use across the Colorado River basin. Changes in temperature and precipitation resulting from climate change are already affecting the timing and overall volumes of runoff and recharge, and these effects are expected to increase in the future. Although an increase in fall season precipitation is anticipated in most parts of the state (related to a projected increase in extreme events associated with hurricane and tropical cyclone activity), higher temperatures will increase evaporative demand (**KM** 2.8).

The anticipated reduction in average winter precipitation at high elevations is expected to decrease runoff and recharge. Both climate change and changes in vegetative cover affect the water cycle, with more dramatic changes due to both factors at higher elevations. This is because there is very little moisture available at lower elevations, which constrains both evaporation and transpiration (**KM** 2.9).

Recharge Across Diverse Landscapes

Mechanisms for capture of rainfall/snowmelt and recharge differ across Arizona's three physiographic provinces (i.e. the Colorado Plateau, Mogollon Rim [Transition Zone], and Basin and Range) due to differences in climate, vegetation, and hydrogeology. While large-scale (mostly constructed) recharge facilities have been located primarily in the Basin and Range province due to proximity to water supplies and demand centers, there are focused areas across the state with considerable recharge potential that warrant additional consideration, such as ephemeral washes, mountain-fronts, areas with karst topography (**KM** 3.10) and landscapes with high incidence of faults and fractures (**KM** 3.11). Controlled tracer experiments in these karst settings can empirically validate subsurface connectivity and be used to quantify transit times critical for recharge management (**KM** 3.12). Diverting surface runoff to the vicinity of surface features such as karst and faults/fractures at higher elevations in the state can translate to increased recharge and base flow that may benefit downstream water users experiencing supply/demand imbalances. Because some of the water that is initially recharged to the aquifers drains out of the aquifer as base flow or is captured by groundwater pumping or evapotranspiration, groundwater storage may be stable or declining even in areas with substantial volumes of recharge.

It is important to note that not all water that infiltrates into the ground reaches the saturated zone or becomes recoverable groundwater. The time it takes for infiltrated water to travel to the aquifer can vary widely (days to hundreds of years) across Arizona's groundwater basins. While travel time to the aquifer may inhibit the recoverability of infiltrated water, water that remains in the vadose zone (unsaturated zone) can still support ecosystem health and provide benefits such as localized zones of saturation and increased soil moisture. Modeling and observations indicate that the amount of water that reaches the water table is influenced by a range of conditions, including soil properties, vegetation type, and ponding time at the surface (**KM** 3.1). Ecological disturbances driven by increasingly hot and arid conditions, such as landscape-wide tree mortality and wildfires, are already affecting quantities and locations of capturable water in Arizona's forests. With the amount of land area burned increasing, pre-fire watershed protection and flood control efforts can facilitate water harvesting and limit potential storm damage from post-fire runoff events (**KM** 3.3).

GIS-based analyses were used to determine where the most suitable surface and subsurface conditions for enhanced capture and recharge projects are located across the state (Statewide Suitability Analyses). Integrating GIS layers such as vegetation density, soil properties, topography, and other factors in different weighted combinations has generated a powerful tool for evaluating capture and recharge suitability. The ATUR team conducted initial suitability analyses for flood enhanced recharge (**KM** 3.9), and forest thinning (**KM** 3.8). In addition, the team evaluated the potential to enhance recharge by directing water to areas with high porosity, such as karst (limestone, etc.) (**KM** 3.10) and developed a statewide lineament (faults and fractures) map because these areas have extremely high recharge potential (**KM** 3.11). ATUR conducted a field experiment to assess the rate of recharge in one area near Flagstaff and found that water reached the regional aquifer within days (**KM** 3.12).

Strategically integrating efforts to enhance infiltration and recharge with ongoing land management and fire management activities, such as optimizing forest patch size and patterns for snow accumulation and persistence (**KM** 3.2) while thinning in areas highly suitable to recharge, may result in the greatest co-benefits for both local communities and downstream water users with little additional cost to land managers.

Analyses of enhanced capture and recharge opportunities were also conducted for urban areas of the state. Watersheds adjacent to and within Arizona's largest cities are projected to experience increased impervious cover due to urbanization through 2100, generating greater quantities of stormwater and opportunities for capture, particularly during winter months, in the Phoenix, Pinal, and Tucson AMAs (**KM** 3.4). ATUR research has found that drywells and retention/detention ponds can be successful strategies to manage and capture stormwater for recharge in these urbanizing regions, with existing features currently capturing over 35% of the total runoff generated in the Phoenix AMA (**KM** 3.6). Working with flood managers and exercising the existing authorities of Arizona's Flood Control Districts may allow for increased integration of recharge opportunities into floodwater management practices and provide both community and ecosystem benefits (**KM** 3.5). While research linking green stormwater infrastructure (GSI) to groundwater recharge, particularly in areas with deep water tables, is limited, models and studies show that GSI such as roof runoff harvesting, rock detention structures, and retention basins can reduce peak flows while increasing infiltration and/or providing water for landscape irrigation demands in semi-arid and arid regions (**KM** 3.7).

In the context of evaluating alternative capture and recharge strategies, it should be noted that there are consequences associated with capturing water to enhance recharge. Environmental assets should be proactively inventoried and protected in the context of any proposed new capture and recharge projects. The ATUR team recommends small-scale pilot projects to test alternative land treatments and capture/recharge strategies.

We developed the term Opportunistic Recharge Enhancement, or ORE, to describe a broad spectrum of land use and resource management activities that can be modified in relatively limited ways to increase the capture of water that would otherwise have evaporated, while enhancing the volume of water that can be recharged. The concept is to integrate recharge objectives into a range of management actions, such as forest thinning to reduce fire risk, land use planning, road construction and maintenance, or management of floodflows. Working in partnership with resource managers, there are numerous opportunities to enhance recharge and achieve other co-benefits through minor changes in design, changes in land use ordinances or practices, or modification of project management activities (**KM** 3.13).

Decision Support Framework

The scientific information developed through this project has been integrated into a decision-support framework (see Section 4, Appendix E, and this interactive StoryMap) for resource managers working to address water adequacy for both human and environmental uses. The framework incorporates the project's key findings and tools into a screening-level flow chart that considers groundwater recharge/management objectives, scale and location, available water sources, recharge threshold criteria, capture and recharge opportunities, and potential costs, benefits, and limitations. The intent of this framework is to provide a roadmap to link our products to decisions and resource managers may be considering at multiple scales. This framework does not address all possible paths to enhanced recharge outcomes but will hopefully help with designing an approach to addressing particular challenges. A consistent theme in our discussions with stakeholders, Tribes and resource managers has been the opportunity for potential cross-sector partnerships, as watersheds and groundwater basins consistently span various management jurisdictions. Section 4 includes a list of these identified partnerships and opportunities for collaboration that may facilitate land use and management decisions, permitting, and funding options for implementing enhanced capture and recharge strategies.

Scale and Uncertainty

The ATUR datasets were produced at spatial resolutions of approximately 1–4 km for historical water balance variables and ~9 km for climate projections. At these resolutions, the data are most reliable for identifying regional patterns, basin-scale differences, and long-term trends, rather than site-specific conditions.

The National Water Model (NWM) outputs used in this project have been rigorously evaluated against observations (stream gauges, eddy covariance flux towers, and snow telemetry stations) across Arizona. A peer-reviewed paper documents this effort (Moiz and Mascaro, 2026). These evaluations show that model performance is highest in snowmelt-dominated basins in central and northern Arizona, particularly during winter, and lower in monsoon-dominated regions and for low-flow conditions.

The Noah-MP simulations used in this study rely on similar land-surface modeling physics and have been evaluated by comparing them with available observations (e.g., evapotranspiration seasonality, snow processes, and runoff patterns) within this project. While a formal statewide validation comparable to the NWM study is not available, consistency across multiple forcing datasets and agreement with observed large-scale patterns provide confidence in their use for regional assessments.

Overall, confidence is highest for:
- Basin- and regional-scale patterns
- Seasonal variability and long-term trends
- Changes in temperature

Uncertainty is higher for:

- Local-scale estimates
- Precipitation magnitude and intensity (especially monsoon and tropical storm related events)
- Recharge processes, which depend on local conditions

These datasets are therefore best suited for screening-level analyses and regional prioritization, while site-specific decisions should incorporate additional local data and investigation.

Data Gaps and Future Research

The ATUR project has produced a statewide, scientific foundation to support prioritization of areas to explore capture and recharge options in Arizona. Further analyses are warranted to translate screening-level assessments to site-specific considerations. Additionally, Arizona is a big state with a relatively low density of monitoring networks. Expanded observational networks and field campaigns, particularly measuring/monitoring groundwater levels and evapotranspiration in areas of interest/concern across the state, would be helpful to reduce the uncertainty inherent in AI-augmented modeling, remote-sensing, and GIS-based analyses and would allow for improved model calibration and validation. Hydrogeology is also a key factor, and field observations such as groundwater levels and subsurface geology are very limited. With increased observational datasets, future analyses could include improved estimation of volumes of captured/stored water associated with different management strategies, identification of the fate of recharged water, spatial definition of areas with supply/demand imbalances, and calculation of water available for capture and recharge using specific methods in identified locations.

ATUR Final Report Key Messages

(Supporting Information and Primary Contributors for Each Key Message are Available in Appendix D)

Key Message	Key Message Summary
2.1	Current water balance information has been estimated using a suite of high-resolution models and confirmed through observations for the 51 ADWR-designated groundwater basins and HUC-8 surface sub-basins in the state.
2.2	Evapotranspiration (ET) is the dominant water loss in Arizona's water balance, accounting for more than 95% of annual precipitation statewide. Consequently, even modest reductions in ET could translate into meaningful increases in water availability for direct use or groundwater recharge.
2.3	Natural groundwater recharge represents a small fraction of Arizona's water budget, accounting for less than 3% of average annual precipitation statewide. However, recharge rates vary substantially across the state's groundwater basins, ranging from less than 1% in the Basin and Range province to more than 10% of annual precipitation in individual basins along the Mogollon Rim.
2.4	Based on modeling results, groundwater recharge generally peaks in early spring in Arizona due to snowmelt in mountainous areas. However, recharge peaks later (May–June) on the Colorado Plateau.

Key Message	Key Message Summary
2.5	With some exceptions, higher precipitation intensity increases the rate of groundwater recharge, especially during the summer; however, there is an optimum range of precipitation intensity for recharge because on-site recharge can be limited if a large proportion of the precipitation becomes surface runoff.
2.6	Base flow, or the portion of streamflow sustained by groundwater discharge, accounts for approximately 32% of average annual streamflow in Arizona, with substantial variation across the state. Tracking changes in the base flow component of stream flow over time can help water managers understand how changes in climate are affecting groundwater contributions to streamflow and is a particularly useful tool for regions with limited direct groundwater monitoring.
2.7	ATUR model estimates show that climatic factors can explain much of Arizona’s terrestrial water storage (TWS) declines since 2000 (2000–2020). Our model-based TWS depletions are consistent with GRACE gravity-based observations (which incorporate all reductions in water supplies, including both groundwater pumping and climate-driven depletion).
2.8	Ensemble modeling of Arizona's water cycle under a relatively high emissions scenario (SSP 3-70*) projects robust and continuing temperature increases, alongside decreasing runoff and groundwater recharge, driven by rising evaporative demand and precipitation declines concentrated in the state's high-elevation water source areas.
2.9	Vegetation change alters the hydrologic cycle by modifying evapotranspiration and runoff, with stronger effects on precipitation partitioning at higher elevations. In the future climate–land cover scenario tested, most projected hydrologic changes are driven by climate, while vegetation shifts produce localized impacts, particularly at high elevation.
3.1	Generally, the controlling factor for inducing recharge is the movement of water vertically, past the root zone. Saturated conditions at the ground surface (surface ponding) lead to much higher vertical water flux. The ponding duration required to initiate recharge depends on local conditions and is challenging to predict and difficult to measure directly. There is a substantial decline in recharge feasibility in soils with greater than 20% clay content.
3.2	Forest thinning has been shown to reduce both ET and sublimation losses (direct loss of snow to evaporation). It can enhance water availability through increasing the snow water equivalent (SWE), raising the liquid water input (LWI), and/or reducing sublimation. Some post-thinning forest patch size and geometry combinations enhance snow accumulation and persistence more than others. These benefits increase water availability, but the quantity of potential capture and recharge depends strongly on local climate and geology.
3.3	Ecological disturbances driven by increasingly hot and arid conditions, such as landscape-wide tree mortality and wildfires, are already affecting quantities and locations of capturable water in Arizona’s forests. Pre-fire watershed protection and flood control efforts can potentially facilitate water harvesting and limit potential storm damage from post-fire runoff events and associated large-scale erosion.

Key Message	Key Message Summary
3.4	Land use changes in watersheds adjacent to and within large cities are projected to result in increased impervious surface due to urbanization through 2100 in the Phoenix, Pinal and Tucson AMAs, with potential to generate greater quantities of urban enhanced runoff (UER), particularly during winter. This increase in UER presents opportunities for capture and recharge because this water is not yet appropriated and the majority of it would otherwise have evaporated.
3.5	Working with flood managers and exercising the existing authorities of Arizona's Flood Control Districts may allow for increased integration of recharge opportunities into floodwater management practices and provide both community and ecosystem benefits.
3.6	Drywells and retention/detention basins are strategies to manage and capture stormwater for recharge in urban regions. In the Phoenix Active Management Area, the ATUR team estimates that over 94,000 acre-ft per year (over 35% of the total runoff generated) on average was captured and infiltrated annually from drywells and retention basins from 2010–2020.
3.7	Research linking green stormwater infrastructure (GSI) to groundwater recharge is limited. However, models and studies show that GSI practices such as roof runoff harvesting, rock detention structures, and retention basins in semi-arid and arid regions can reduce peak floodflows while increasing infiltration and/or providing water for landscape irrigation demands.
3.8	Statewide mapping shows that forest thinning in Arizona’s ponderosa pine forests can enhance recharge and provide a water-capture co-benefit. Of the 1.4 million hectares of ponderosa pines statewide, about 46% (588,992 ha, 1.45 million acres) is highly suitable and 2.4% (30,920 ha, 76.5 million acres) is very highly suitable for thinning with recharge enhancement as co-benefit.
3.9	The statewide suitability tool for the use of floodwaters to enhance recharge allows identification of regions with high recharge potential. It can provide justification for more targeted local surveys to quantify actual recharge and inform local management practices.
3.10	Karst aquifers (including limestone and related rock types) are critical to Arizona’s water resources; they support municipal water supplies, sustain base flow in rivers and streams, and feed ecologically important springs. Karst landscapes—characterized by internal drainage, rapid infiltration, and direct connection between surface and groundwater—offer unique opportunities for recharge enhancement.
3.11	Lineament density (density of fault-related features) is a widely used indicator of enhanced infiltration potential and a common factor or thematic layer used in analyses for recharge suitability and in identifying potential recharge zones in bedrock environments.
3.12	Controlled tracer experiments in karst systems provide critical empirical data for managed aquifer recharge design in semi-arid regions, revealing rapid subsurface connectivity through structural features that concentrate recharge—these same features render these zones vulnerable to contamination, presenting a fundamental trade-off for system design.

Key Message	Key Message Summary
3.13	Groundwater supplies can be supported by integrating groundwater recharge considerations into existing land and water management practices. Opportunistic Recharge Enhancement (ORE) is a cross-disciplinary, scalable framework to augment groundwater supplies by strategically integrating recharge co-benefits into existing land and water management practices such as land use planning, forest thinning and stormwater management.

Conclusions

The following is an integrated summary of the project team's conclusions, noting that these relatively simple conclusions can be misleading if they are not taken in the full context of this report. We recommend that these be viewed as a high-level summary, but that actions or decisions that depend on these findings must be considered in light of management objectives, land ownership, water rights, and hydrogeological realities. The leaders of our project are available to assist with interpretation.

1. Warming is having a profound effect on the hydrologic cycle in Arizona, increasing losses to evapotranspiration, reducing soil moisture and decreasing recharge. Statewide, total water in storage is declining over time. Recharge is critical to reliable water supplies.
2. Snowpack-dominated areas are experiencing the most significant changes, including reduced snowpack and earlier peak runoff.
3. More than 95% of the precipitation that falls in the state is lost through evapotranspiration. Reducing ET by even small percentages could yield significant supply increases.
4. There are consequences associated with changing the hydrologic cycle, and it is imperative that environmental assets be protected in the context of any proposed new capture and storage projects. We have provided a section called "Guiding Principles for Enhancing Recharge and Habitat" to address this issue.
5. There is strong evidence that extreme events, including heat waves, drought, floods and wildfires will increase in intensity over time. Flood-related extremes may provide new opportunities as well as new challenges. Engaging flood control districts in partnerships to maximize capture and recharge of increased flows is one option that can be considered.
6. Changes in precipitation intensity and frequency affect recharge rates.
7. Land management decisions at multiple scales can be adjusted to take advantage of a new framework proposed in this report: Opportunistic Recharge Enhancement. This involves integrating recharge considerations into fire management, road-building, land and infrastructure development, flood control and other resource management activities.
8. There are a multitude of capture and recharge options available that are identified in the Capture and Recharge Opportunities Matrix (see Appendix F).

9. Drywells and detention basins appear to be much more effective at inducing infiltration than has been previously recognized. Although additional monitoring of actual aquifer impacts associated with these features is warranted, initial evidence is strong.
10. Increasing the length of time that floodflows are held in retention basins, though discouraged due to concerns about insect vectors, is likely to increase recharge rates.
11. Thirty-two percent (32%) of surface water flows in the state originate as groundwater outflow; while surface water recharges groundwater basins in other areas. These fundamental aspects of water in Arizona are not well recognized by the public or by our existing legal system, which treats surface water and groundwater as if they were separable.
12. Considering the dramatic implications of water supply issues statewide, there is a significant need to strategically expand monitoring so that there is better evidence of changes in groundwater levels, real-time monitoring of surface water flows in more locations, and measuring evaporation/transpiration across multiple land cover types.
13. The water supply information that is provided for each basin in this report provides a great starting point for more detailed water supply and demand planning activities. More work is needed to evaluate potential next steps.
14. Partnerships will be critical to move quickly towards more reliable water supply conditions. In particular, it is important that federal agencies and Tribes, who collectively manage the largest percentage of the Arizona landscape, be directly engaged in these activities.
15. We strongly suggest that resource managers test the Decision Support Framework we have provided. We believe that following this step-by-step process may lead to some surprising and innovative solutions. **In the absence of this kind of "decision-tree" approach to selecting capture and storage options, here are some general "rules of thumb"**:
    a. The area of the state with the highest potential for generating large volumes of water for capture and storage is the Mogollon Rim/Transition Zone, because of its significantly higher volumes of precipitation relative to ET.
    b. Capturing water before it evaporates can significantly increase water supplies in some locations within the state. Because water evaporates from every basin, there are options for capture in many locations, but volumes generated may be very limited in most of the alluvial basins in the southern and western parts of the state.
    c. There are multiple ways to enhance recharge of water in natural systems across the state. Those that in particular warrant further review are:
        i. an analysis of karst topography and areas of significant rock fissures (with high recharge potential) in the vicinity of potential capture locations
        ii. identification of mountain-front recharge areas that could be enhanced to receive larger volumes of recharge
        iii. improvements in floodplain management practices to maximize capture/retention and recharge, rather than evaporation, of floodflows

    iv. implementation of the Opportunistic Recharge Enhancement concepts mentioned above, including incorporation of recharge objectives as a co-benefit in infrastructure design, particularly road building, forest thinning and, fire management to minimize interception losses and maximize snowpack retention

d. The most productive ways to maximize capture and recharge within urbanized areas are:

    i. Designing capture and recharge into new land development policies in order to maximize urban enhanced recharge and protect areas that naturally have high recharge rates, such as floodplains and ephemeral channels

    ii. Maximizing the use of dry wells for flood control, especially in areas with known connectivity to the regional aquifer

    iii. Promoting retention basins designed for depth over area, with low-clay soils and minimal evapotranspiration by plants to encourage recharge

SECTION 1
INTRODUCTION

Project Motivation and Approach

The ATUR project's main goal is to answer questions from the Arizona Department of Water Resources regarding ways to capture water that is currently lost to evaporation and/or generated through urban development, and where and how that water could be recharged. Answering these questions required that we develop foundational, hydrological characterizations across the state of Arizona, and involved multiple researchers from across the state universities (The University of Arizona, Arizona State University, and Northern Arizona University). The team pursued a multi-pronged research agenda, with investigations into 1) ways in which the natural hydrologic cycle water balance is currently partitioned across the state of Arizona (i.e. via precipitation, evapotranspiration, runoff, and recharge within the state's 51 groundwater basins), 2) management strategies that can influence water balance fluxes, 3) suitability analyses for capture and recharge in different basins, and 4) implications of climate change for future water budgets. ATUR researchers utilized historical observations, hydrological modeling, land surface modeling, remote sensing, climate modeling and GIS-based research techniques as well as input from workshops and expert elicitation. A thorough assessment of existing literature and case studies was conducted relative to each major theme. Multiple studies were conducted across the state and include novel approaches such as machine learning and the enhanced use of publicly available models (e.g. NOAA's National Water Model, the Noah-MP land surface model, and bias-corrected evapotranspiration and climate models (see Appendix I: Glossary for additional information) that have not previously been used to characterize Arizona's water supplies.

Many opportunities for enhanced capture and recharge were identified across Arizona's diverse landscape types. Each has been described along with an initial identification of potential limitations and environmental impacts (see Appendix F: Recharge Opportunities Matrix). Some of these management options (e.g. flood-related projects, forest thinning) were considered alongside surface and subsurface analyses statewide and evaluated using a GIS-based approach to characterize their suitability for enhancing groundwater recharge (Statewide Suitability Analyses). The results of these studies, conducted at multiple scales (e.g. statewide, regional, and groundwater basin scales) are summarized throughout this report and included in the form of key messages.

In addition to technical investigations, the study has employed a robust stakeholder engagement process that includes regular meetings with ADWR and the project's Technical Advisory Committee, as well as stakeholders representing a diversity of perspectives and interests that include local, state, and federal land and water managers, scientists, Indigenous communities, and NGOs, to ensure relevance and utility of project deliverables to ongoing work throughout the state and to support identification of potential future project partners. In all, the team conducted nearly 90 meetings and workshops with more than 80 organizations and individuals. In most cases, these entities and individuals engaged with us multiple times. Their input has been critical to our approach and our findings.

Report Format

Significant results and insights from ATUR project studies relevant to groundwater management are summarized as **Key Messages in Sections 2 and 3**. Each Key Message presents a study insight (shown in ***bold italics***), followed by a brief description, supporting information, and links to relevant data and literature. The report includes the following sections. In Section 1, an introductory description of Arizona's hydrogeologic conditions is given along with some of the factors associated with groundwater recharge. Section 2 and Section 3 present the primary findings of the project as **Key Messages** related to statewide water summaries and recharge opportunities across diverse landscapes, respectively. Section 4 describes the Decision Support Framework, providing a roadmap for enhancing capture and recharge and integrating the insights of project findings, while Section 5 summarizes data gaps and future research directions.

The report includes several appendices that provide supplementary materials. Appendix A presents summaries of the natural water balance—based on precipitation partitioning only and excluding human activities such as groundwater pumping—for the 51 ADWR groundwater basins (see basin map, Figure 2.2). The primary information in these summaries is historic (based on the 1980–2020 period): Precipitation, Evaporation, Transpiration, Runoff, Recharge for each basin, basin-averaged base flow index, an outline of the basin, size and elevation (average, min, max) of the basin, and projected information regarding changes in temperature and precipitation by month. Additionally, we provide future projections of these variables for each basin. These summaries are intended to facilitate easy access to information relevant to a broad range of users and to support assessment of capture and recharge options for each basin. To our knowledge, this type of information has not previously been available at basin or statewide scales and provides important context for identifying areas where water may be captured and/or recharged. Appendix B lists the publications and datasets produced through this project. Appendix C includes both a summary of the relevant pre-existing literature and a reference list supporting topics in the report. Appendix D includes a simplified version of the **Key Messages** with supporting information for each. The Decision Support Framework and the associated Guidebook and StoryMap is included in Appendix E. Appendix F is the **Recharge Opportunities Matrix**. Researcher Bios appear in Appendix G, and the list of Technical Advisory Committee members are listed in Appendix H. Appendix I is the Glossary. Finally, Appendix J is the Bibliography for this report.

In support of this report, a series of online **StoryMaps** is currently in process; we also provide infographics to illustrate key processes and conclusions associated with the project's focus areas, including hydroclimate modeling, recharge suitability and assessment, natural landscapes, urban landscapes, and stakeholder engagement. These materials are intended to support clear communication of the concepts presented here.

Arizona's Hydrogeologic Conditions

The central focus of the ATUR project is to increase recharge, with a primary goal of increasing the availability of water for human use. However, this goal must be balanced with consideration of the other roles that water plays in the landscape—both potential impacts of increasing

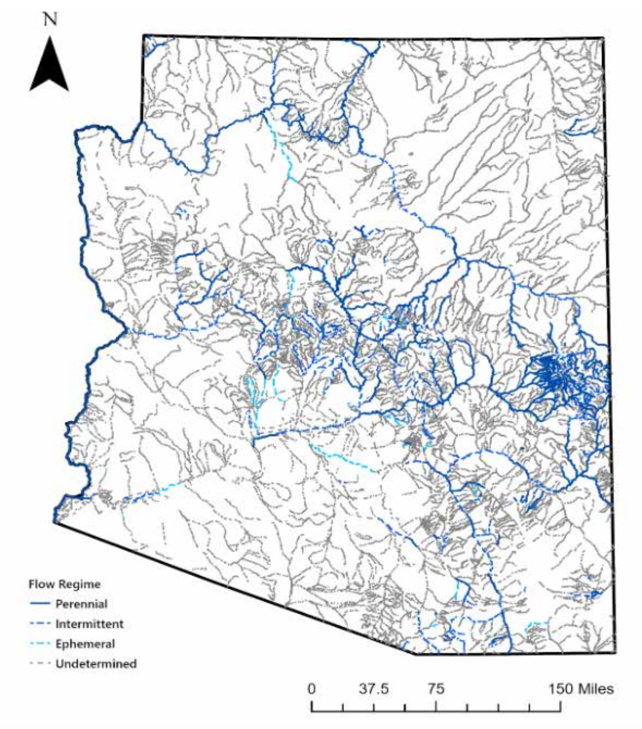


Figure 1.1 Rivers and streams in Arizona shown by flow regime: perennial, intermittent, ephemeral, and undetermined. Many of the formerly perennial stream segments are now ephemeral due to surface water diversions and groundwater pumping. (Source: ADEQ GIS Flow Regimes; Figure Credit: Lima)

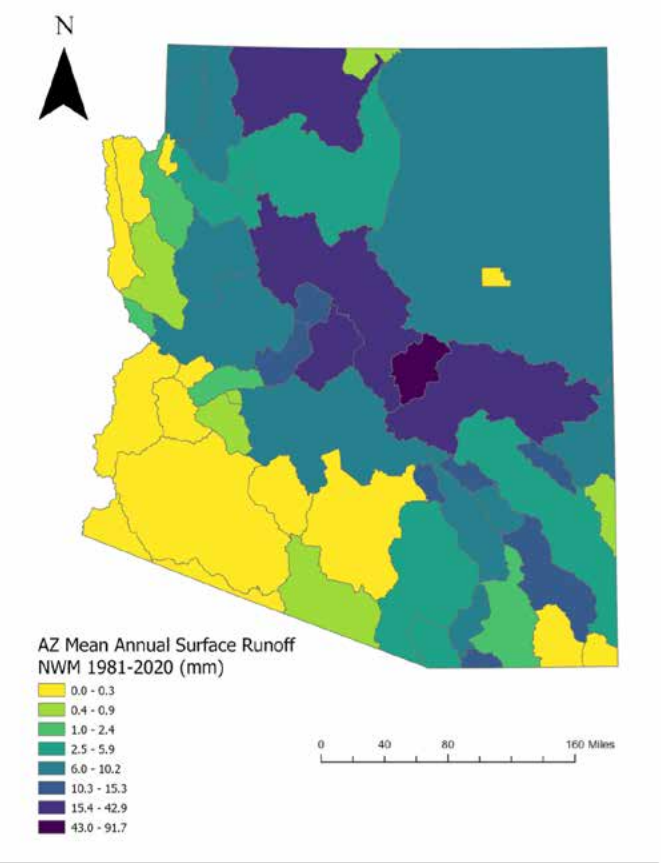


Figure 1.2 Outputs from the National Water Model showing mean annual surface runoff (mm) in Arizona's groundwater basins from 1981-2020 (results averaged across groundwater basins) (Source: Moiz & Mascaro, 2026; Figure Credit: Hinkley).

recharge at the expense of other water uses and potential benefits of recharge beyond human use. This project has explicitly focused on ways to enhance recharge without damaging (and hopefully supporting) natural systems and environmental health.

In much of the state, the amount of surface runoff generated is limited due to lack of precipitation. However, even in the drier basins there can be significant water accumulation at the ground surface in localized impervious areas. These areas include developed urban areas and areas with limited infiltration capacity, such as exposed bedrock and localized clay or other fine-grained materials at the ground surface, or degraded watershed conditions.

Many of the opportunities described in this study are based on collecting and conveying water that might otherwise have been lost to the atmosphere (via evapotranspiration and sublimation) and routing it to areas of high infiltration capacity. In some cases, there is insufficient water available, a lack of highly permeable sediments, or inadequate aquifer storage capacity, limiting the ability to increase recharge. However, some of these areas may support other beneficial uses of infiltrated water, such as supporting ecosystems. Maintaining or enhancing riparian habitat through these mechanisms is a significant objective in many basins, particularly given the dramatic impacts of climate change on water-dependent ecosystems and the major contributions that riparian areas make to biodiversity, recreation, land values, etc.

While ATUR was tasked with conducting a state-wide assessment, no single set of metrics for recharge suitability can be applied across the entire state because of the significant differences in hydrogeology and groundwater conditions. Figure 1.3 shows generalized geology across Arizona. The strong contrast between most of the north-northeast and south-southwest regions of the state is very clear: south of the Colorado Plateau and transition zone, the Basin and Range Province in the southern part of the state has alluvial basins that appear as either isolated or connected “pockets” of deep bedrock whereas the northern part of the state has bedrock at or near the surface. The pockets of deep bedrock originated with stretching of the Earth’s crust, which resulted in faulting of the surface and down-dropping of significant blocks. These areas subsequently filled with eroded alluvium from adjacent mountain blocks; these **alluvial basins** contain most of the groundwater resources exploited by pumping in this state not only because they (not coincidentally) underlie the most populous parts of the state, but also because most of these basin-fill deposits can (and do) store and release vast quantities of groundwater readily extracted by pumping. Depths to water in many of these alluvial basins is less than 300 feet below ground surface (ft bgs) and the depths to bedrock often exceeding 1000 ft, with several thousand ft being the norm. Hydraulic conductivities are generally high, though basin-fill deposits may contain considerable clays and fine-grained materials. Dewatering fine-grained materials such as clays leads to compaction of the aquifer and subsidence of the land surface, which is a major issue across the Basin and Range aquifers (Carruth et al. 2007; Miller et al. 2017; Peng et al. 2022). In many cases when this compaction occurs it is irreversible and leads to a permanent loss in storage.

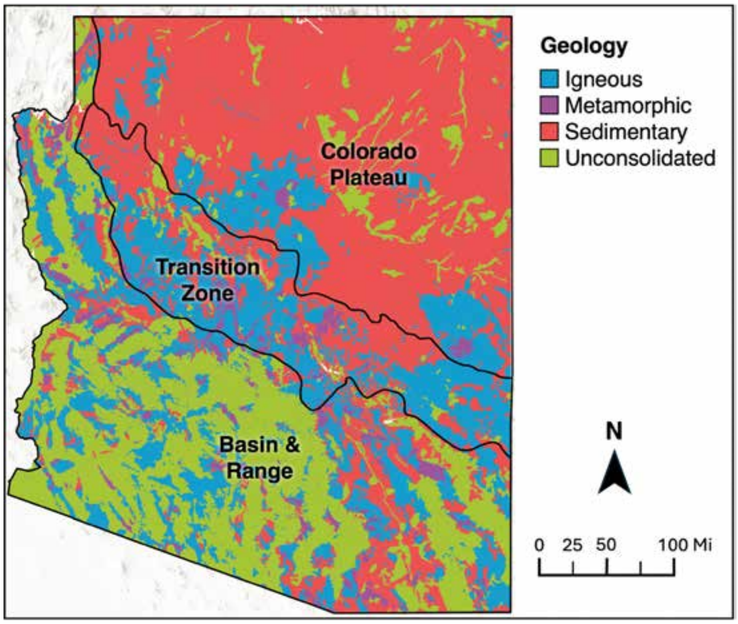


Figure 1.3 Arizona generalized surficial geology and physiographic regions. (Source: State Geological Map Compilation (surficial geology); Figure Credit: Mroczek)

In the Colorado Plateau and Transition Zone, nearly all groundwater occurs in rock formations rather than in unconsolidated sediments though there are smaller alluvial basins, such as the Tonto Basin, that support wells in the Transition Zone. Productive **hard-rock aquifers** occur in various types of formations (e.g., sedimentary, volcanic, and intrusive igneous). In some areas, secondary porosity from fractures, faults, jointing, weathering, and dissolution karst (e.g., limestone and other high porosity features) provide highly transmissive aquifers. However, capacity to store water in hard-rock aquifers may be very limited, causing groundwater supplies to be vulnerable to rapid depletion by pumping. Successful development of groundwater wells in hard-rock aquifers often depends on intercepting natural faults and fractures and can be financially risky. Depths to water vary significantly across the Colorado Plateau and Transition Zone areas. In some areas, clay layers may maintain groundwater at less than 300 ft below ground surface (bgs), but in other cases, extensive groundwater production zones may be more than 2000 ft bgs. In some areas near the Colorado River and along the Transition Zone, some water bearing units have drained out over time and are now unsaturated.

Recharge Implications

The two main geologic regions discussed above also have distinct recharge mechanisms and histories. Much of the groundwater in the Basin and Range province was stored more than 10,000 years ago during a wetter and cooler climatological period. The elevation contrast between the mountains bounding the basins and the valley floors between the mountains helps drive orographic (elevation-based) cooling, leading to higher precipitation that flows down into the basin-fill sediments primarily along alluvial fans near mountain fronts or through ephemeral channels toward the basin low point. High hydraulic storativity values in these sediments makes them excellent catchments for recharge where groundwater is sufficiently deep (beyond the root zone). Still, natural recharge occurs only where sufficient downward pressure from surface water can overcome the negative pore pressure (upward) that exists in much of the vadose zone soil. Water that does penetrate beyond roughly the top 10 meters (also referred to as the "root zone") may still take years or decades to drain into an underlying aquifer. In some cases, clay lenses under stream channels may impede downward movement or "perch" groundwater for several days or weeks, thereby sustaining surface flows after precipitation has ended.

Hard-rock aquifer recharge occurs through different mechanisms. Driven largely by snowmelt on the Colorado Plateau, significant infiltration through jointing, faulting, sink holes, or karst features near the surface may convey surface water to significant depths fairly quickly in some

Managed Aquifer Recharge (MAR)

Managed Aquifer Recharge (MAR) is a form of artificial recharge. MAR techniques involve the intentional storage of water in an aquifer for subsequent recovery or environmental benefits. Most MAR projects in Arizona occur in the Basin and Range province and are proximal to either a large population center or the CAP pipeline, or both. Recharge projects in the Prescott AMA and in Payson are examples of MAR in the Transition Zone. Payson's system exploits a heavily fractured granitic aquifer while Prescott makes use of a local basin-fill aquifer (the Little Chino). Payson's MAR is unique in that it receives water from a reservoir on the Mogollon Rim that is directed down the East Verde River to a location where Payson can divert it. Significant recharge efforts in the San Pedro River basin have focused primarily on supporting riparian and aquatic habitat to offset groundwater level declines caused by human use.

areas (Tobin et al. 2018). Streams may also flow in response to precipitation from large frontal or convective storm events, thereby moving water across rock-bottomed stream channels for many miles before encountering a recharge area in suitable hard rock or alluvial fill material.

Fate of Recharged Water

Water held in storage in alluvial basins may eventually exit the basin in several ways: a) if groundwater levels are high enough, groundwater may discharge to the ground surface as a spring or contribute to streamflow; b) if groundwater in a neighboring, connected groundwater basin is sufficiently low, groundwater may flow by gravity out of the basin as groundwater "underflow"; c) groundwater may be extracted by pumping; and d) groundwater in the top ten meters or so may be consumed by evapotranspiration. Much of the groundwater stored deep in these basin-fill deposits is "ancient" and has no means of exiting the basin other than via pumping.

Groundwater in hard-rock aquifers may, in some instances, occur in isolated blocks where it is bound by low-permeability faults and/or rock formations. For example, in the Transition Zone below the Mogollon Rim in eastern Arizona, isolated blocks of Coconino Sandstone and upper Supai formation sandstone store groundwater at depths less than 300 ft bgs, whereas, north of the Mogollon Rim, the Coconino formation is generally saturated only below 800 ft bgs, if at all. Deep carbonates, such as the Redwall-Muav aquifer system, extend across much of the Colorado Plateau and Transition Zone. This cavernous limestone system hosts large springs that receive recharge from the Colorado Plateau via overlying volcanics and sedimentary layers. Groundwater recharged into the Redwall-Muav may travel rapidly to a discharge point located miles away, discharging to interior river systems like the Salt River and Verde River, or to the Colorado River along the state's north and western borders. Developing wells in this karst system is feasible in some areas, but also may be problematic due to depth to water, difficulty in identifying high well yield zones, and high salinity. Groundwater may also travel through porous media in sandstone and some volcanic materials. Natural discharge from these units may occur where saturated rocks intercept the atmosphere at cliff faces or through slow seeps or springs in stream or river valleys.

In areas with very shallow groundwater levels, recharge tends to follow major precipitation events. In areas with greater depths to water (e.g. hundreds of feet), recharge is often episodic and spatially focused, such as mountain fronts, ephemeral channels, and areas with karst topography. Where these features do not exist, it takes much longer for infiltrated water to reach deeper water tables.

Different Metrics for Different Regions and Purposes

Given the diversity of both recharge environments and objectives, there is no single set of physical site characteristics that can be applied across the entire state to evaluate recharge potential. Therefore, we developed a Decision Support Framework, intended to be a roadmap to help resource managers think through the options that are available at different scales. Examples of options worth exploring for recharge potential are:

- **Forest thinning**: Forests within the state that are overstocked—or overly dense relative to historical conditions—offer potential for thinning to reduce ET and increase the amount of water available for recharge. Forest thinning is also used to reduce fire risk near and within communities.

- **RoadMAR**: Opportunities exist to intercept rainwater from roads that act as slope breaks disrupting surface and shallow soil flow, and recharge it through various engineered techniques.
- **Mountain fronts**: Low-lying flat areas adjacent to high relief areas may be suitable locations to capture flood water during extreme precipitation events. This retained water can reduce flood risk and could be recharged through retention/detention basins, dry wells, or other engineered structures.
- **Urban Areas**: Development that increases impervious area creates additional runoff which could be funneled to pervious areas for infiltration or into dry wells. Dry wells have been shown to infiltrate large amounts of water in the Phoenix metro area.
- **Karst topography**: Areas underlain by karst often contain features which can facilitate rapid recharge; however, the rapid rates of recharge in these areas may in some circumstances increase the risk of contamination.

Distinguishing Between Infiltration and Recharge

It is important to note the distinction between water that infiltrates only into the vadose (unsaturated) zone from water that actually reaches the saturated zone of the aquifer and becomes “recharge.” While infiltration is necessary for recharge, not all water that infiltrates into the ground becomes recoverable groundwater. That said, there can still be benefits to water remaining in the vadose zone because it may be available to deep-rooted plants and support ecosystem health. Water that occurs deeper in the vadose zone may eventually flow to the saturated zone under the pressure of additional water moving into the vadose zone. Protecting or enhancing groundwater recharge in selected areas that may receive higher annual precipitation can increase groundwater storage and benefit stream base flows, riparian and wetland habitats, and human water users that are down gradient or in downstream locations.

SECTION 2

STATEWIDE WATER SUMMARY

As described above, Arizona's hydrogeology exhibits substantial spatial variability. Likewise, the state shows pronounced spatial and seasonal variability in climate, vegetation, and landscape characteristics, ranging from desert scrub in valley lowlands to conifer forests in snowy, mountainous regions. This heterogeneity leads to dramatic differences in hydroclimatic conditions across the state. Quantifying the spatial and temporal variability of hydroclimatic conditions, both in the historical climate and under different global warming scenarios, is therefore critical for supporting water resources management and augmentation.

Motivated by this need, the ATUR team has worked to better understand and communicate the nuances of Arizona's hydroclimate across a range of scales. Key messages emerging from this effort are summarized below. These insights were generated through analysis of ATUR modeling results and synthesis of existing studies, with a primary focus on the spatial and temporal characteristics of groundwater. Climate influences were examined both in terms of variability within the historical record and projected impacts on the hydrologic cycle and natural vegetation under future climate conditions. Land surface models were used to estimate the natural water budget of the hydrologic cycle, referred to in this report as the "water budget" or "water balance." The water budgets presented here exclude human demands and activities, such as groundwater pumping, artificial recharge, and inter-basin water deliveries.

Components of the Natural Water Balance across Arizona

Key Message 2.1:
Current water balance information has been estimated using a suite of high-resolution models and confirmed through observations for the 51 ADWR-designated groundwater basins and HUC-8 surface sub-basins in the state.

The ATUR team has estimated long-term monthly means for water years 2003-2022 (October–September) for the basin-averaged Precipitation and Temperature, as well as runoff volume (Q*; see caption under Figure 2.1 for a description of how these averages were computed) in 12 main surface basins located entirely or partially within the state of Arizona (Figure 2.1). These basins were obtained by aggregating 84 hydrologic unit code 8 (HUC-8) level sub-basins (Moiz and Mascaro, 2026) (see map of HUC-8 units, Figure 2.2).

Temperatures follow the general climate pattern of the northern hemisphere, with the maximum occurring in July or August and the minimum in December or January, and the mean being controlled by elevation. Precipitation exhibits two peaks: one in winter between December and January when P is caused by cold fronts from the Pacific Ocean, and the other in summer (July–August).

Monthly Climatologies of Precipitation (P), Temperature (T), and Discharge

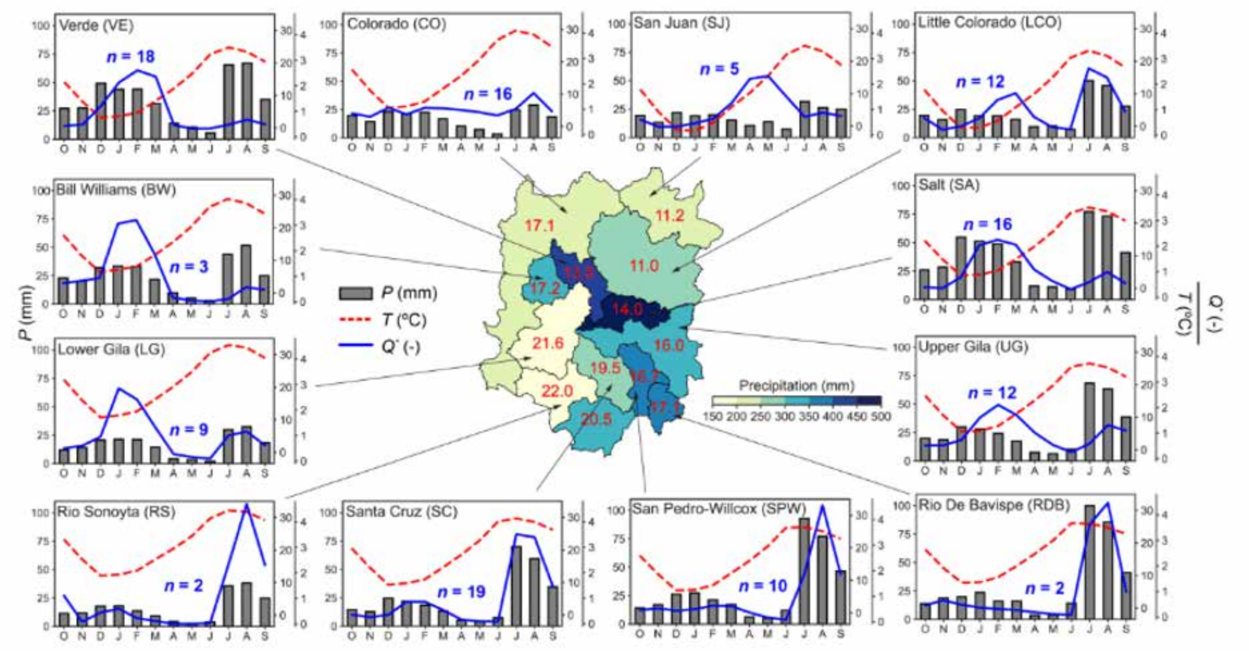


Figure 2.1. Monthly climatologies of precipitation P (mm), air temperature T (°C), and dimensionless discharge Q* (–) in the 12 analyzed basins in Arizona. P and T are the long-term averages (2003–2022) of the mean areal values of the 1-km Analysis of Record for Calibration (AORC; Fall et al. 2023) gridded products. Q* was computed using the daily discharge (Q) observations at the United States Geological Survey (USGS) gauges within each basin (their number n is reported with blue text) as follows: (1) for every gauge, the long-term (based on data availability) mean monthly Q was computed and divided by the annual mean; and (2) the resulting dimensionless monthly discharges were then averaged. As a next step, three sets of reconstructed water budgets (hydrologic fluxes) were generated in the state of Arizona at high spatial (1 and 4 km) and temporal (1 hour) resolutions for 1980–2020 using two land surface models. Model outputs were compared with observations, aggregated at different scales, and made available for download. (Source: Moiz & Mascaro, 2026)

Land surface models are numerical tools that simulate the exchanges of water and energy at the land surface by representing processes such as soil moisture/temperature changes, evapotranspiration, runoff, and snowpack, driven by meteorological inputs including precipitation and temperature. Outputs of land surface models are helpful because they provide physically consistent estimates of key hydrological and energy variables that are difficult or impossible to observe at basin scales. In particular, they quantify water and energy states and fluxes (e.g., soil moisture, soil temperature, evapotranspiration, runoff, snow-water equivalent, snowmelt) at spatial and temporal scales relevant for hydrologic applications. As such, they (1) support water resources management and hazard assessment, including drought monitoring, flood forecasting, and irrigation planning; and (2) provide spatially and temporally continuous simulations of hydrologic variables for analysis, comparison with other models, and impact studies, even in data-scarce regions.

As previously mentioned, land surface model simulations account only for natural processes and do not incorporate human interventions, notably irrigation; they are less accurate in urban regions.

Explanation of modeling approach used to estimate the historical water balance for each groundwater basin:

The two statewide land surface models used were

1. The community Noah Multiparameterization Land Surface model (Noah-MP) (Niu et al., 2011), with recent modifications from University of Arizona researchers to incorporate a deep soil column (up to 200 meters) and the effects of differences in soil structure that affect moisture flows, e.g., macropores caused by presence of organic matter and rocks in the soil (Niu et al., 2024). Noah-MP was applied at 4-km, 1-hour resolution, and

2. The National Oceanic and Atmospheric Administration (NOAA) National Water Model (NWM). The NWM was designed to forecast hydrologic and flooding conditions across the country and, as part of the calibration effort, NOAA conducted a retrospective analysis at 1-km, 1-hour resolution from 1981 to 2020, which is used here. The NWM combines an earlier version of Noah-MP with a 2-m soil column (not extending below the root zone) and an underlying "bucket" to represent groundwater storage (or level) and associated water exchange between the bucket and the upper 2-m soil (based on the Darcy Law; Niu et al., 2007) to simulate rainfall-runoff processes and energy budgets, with surface and subsurface routing algorithms.

The simulations with Noah-MP were carried out with three sets of meteorological forcings to assess the impacts of forcing uncertainties on the modeled water budget including recharge. The forcings include (A) the 40-year, 4-km, 1-hour regional hydroclimate reanalysis over the conterminous United States (CONUS) from the National Center for Atmospheric Research (NCAR), known as CONUS404, (B) the 1-km, 1-hour Analysis of Record for Calibration (AORC) dataset produced by NOAA, and (C) AORC with its precipitation being replaced by the Integrated Multi-satellite Retrievals for GPM or IMERG precipitation. The retrospective analysis with the NWM was produced by NOAA for the entire CONUS using the AORC forcings. We obtained their outputs for Arizona and systematically compared them against observations to verify their accuracy and utility.

Key variables of the water budget, including precipitation, evapotranspiration, surface runoff, and recharge, were processed to create long-term statistics (e.g., mean, standard deviation, and coefficients of variation) at seasonal and annual scales. This effort produced output files at the model resolution (1- or 4-km) and shapefiles containing basin-averaged quantities for Hydrologic Unit Code (HUC) 8 basins and 51 ADWR-defined groundwater basins in Arizona, to facilitate use by land and water managers (Figure 2.2). For example, maps of the mean annual total for mean annual precipitation, evapotranspiration, and surface runoff simulated by the NWM in HUC-8 basins in Arizona are shown in Figure 2.3.

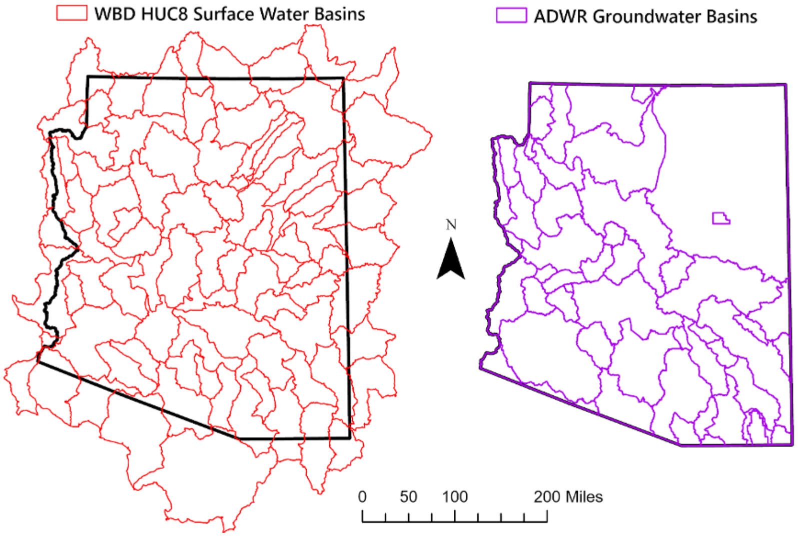


Figure 2.2. Arizona surface water basins HUC08 (left) from the Watershed Boundary Dataset (WBD). Arizona's 51 Groundwater basins as defined by ADWR (right). (Figure Credit: Lima)

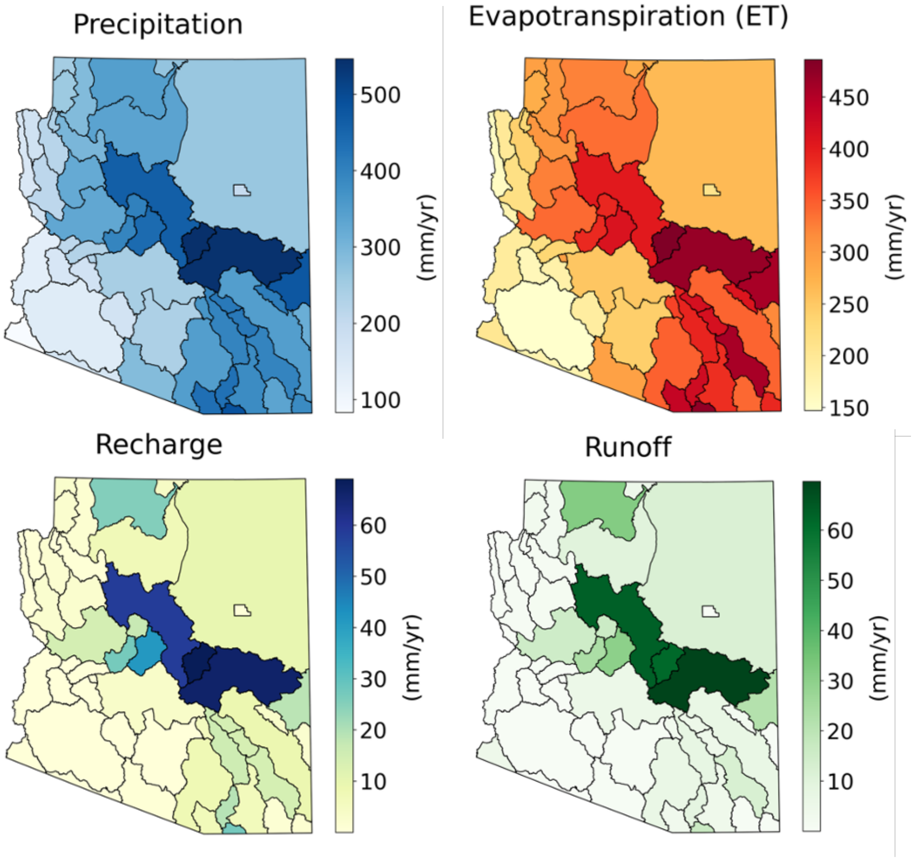


Figure 2.3. Mean annual precipitation, evapotranspiration, recharge, and runoff in 1980–2020 water years simulated by Noah-MP in ADWR Groundwater Basins. (Source: A. Gupta, 2026; Figure Credit: Hinkley)

A significant contribution of the ATUR work is validating the NWM results using observational data from USGS stream gauges, eddy covariance flux tower data, and snow telemetry stations (Moiz and Mascaro, 2026). Comparisons with observational data showed that runoff is modeled better in central and northern Arizona watersheds dominated by winter precipitation and snowmelt than in monsoon-dominated watersheds in southern Arizona. The seasonality and daily variability of ET are captured very well by the NWM, which is notable given that ET is the most significant non-precipitation component of the water balance across Arizona. Snow water equivalent is also modeled well on a seasonal basis, although it has a negative bias that increases with elevation. Collectively, these analyses clarify the strengths and limitations of the NWM across Arizona, providing water managers with guidance on the appropriate use of NWM outputs to evaluate spatial and seasonal patterns in key components of the water balance.

The Role of Evapotranspiration

Key Message 2.2:
Evapotranspiration (ET) is the dominant water loss in Arizona's water balance, accounting for more than 95% of annual precipitation statewide. Consequently, even modest reductions in ET could translate into meaningful increases in water availability for direct use or groundwater recharge.

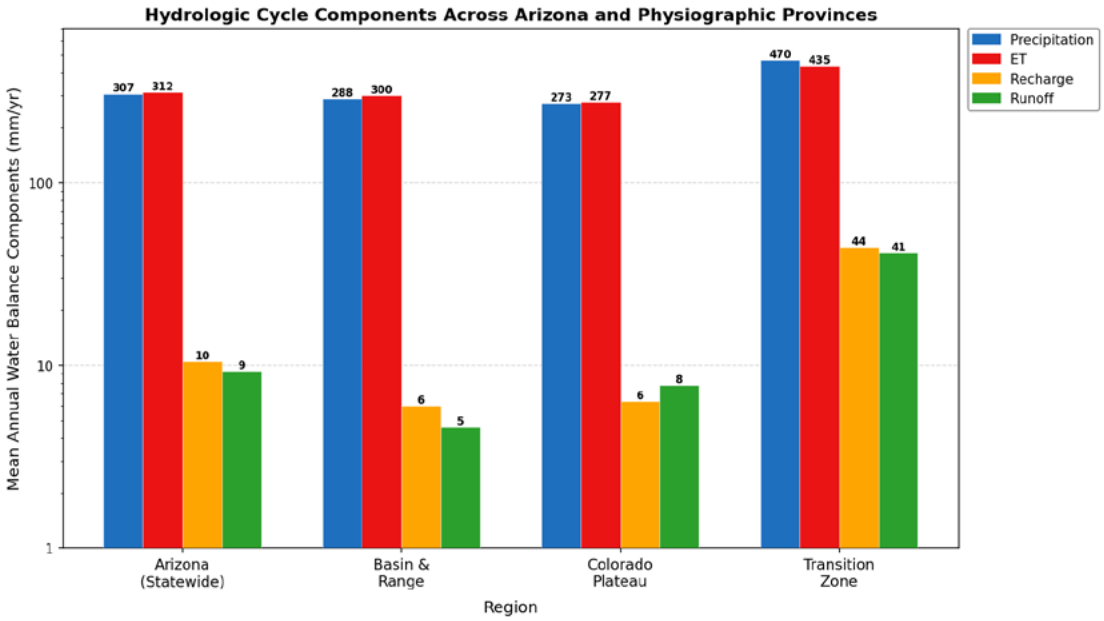


Figure 2.4. Noah-MP modeling results illustrate the historical mean annual precipitation [P], evapotranspiration [ET], natural recharge, and runoff) across Arizona (first set of bars) and each of the Physiographic Provinces from 1980-2020. The y-axis is displayed on a logarithmic scale to accommodate the large differences in magnitude across hydrologic components. On average statewide, in the Basin and Range and the Colorado Plateau provinces, results show that ET is greater than P on annual timescales. It is possible for ET to be greater than P when there are other sources such as groundwater, surface water, or water in storage that evaporates or transpires. The Transition Zone / Mogollon Rim is the region of the state with the highest potential for generating large volumes of water for capture and storage due to its higher volumes of P relative to ET. (Source: A. Gupta, 2026; Figure Credit: Mohsenzadeh Karimi)

Our analyses, together with the existing literature, confirm that ET is by far the largest component of water loss in Arizona, accounting on average for more than 95% of annual precipitation. Quantifying the spatial and temporal variability of ET has therefore been a central objective of this project, as understanding ET patterns is essential for evaluating strategies to enhance water availability and recharge.

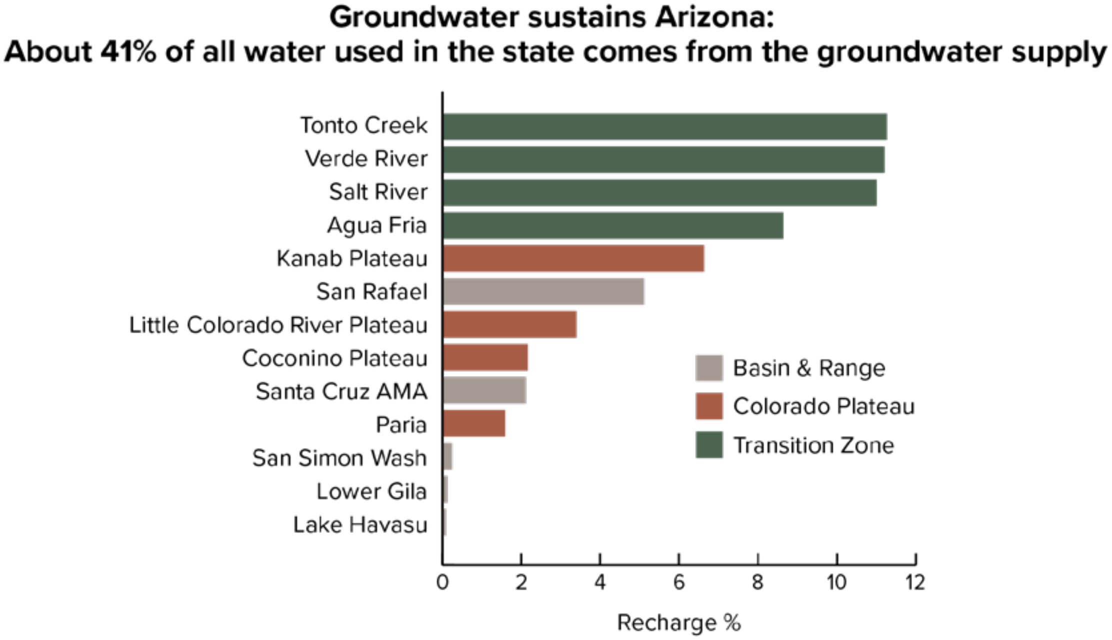


Figure 2.5. Estimated percent of precipitation falling within selected groundwater basins that becomes groundwater recharge. Colors denote location of each basin within the physiographic provinces. (Source: A. Gupta, 2026; Figure Credit: Mohsenzadeh Karimi).

Because no instrument directly measures ET over multiple spatial scales, the ATUR team estimated ET using a combination of land surface modeling and remote sensing products, including:

- Hourly outputs from the Noah-MP and NWM land surface models at 4- and 1-km resolution statewide.
- Daily outputs from the USDA's Soil & Water Assessment Tool (SWAT) hydrologic model (used in targeted basins for testing fluxes in small-scale experiments).
- Three satellite-based ET products available statewide: OpenET (30-m monthly, 2016–present), MODIS ET (1-km 8-day, 2000–present), and ECOSTRESS (70-m daily, 2019–present).

Model-derived and remotely sensed ET estimates were validated against eddy covariance flux tower measurements, which provide accurate ET estimates over footprints of up to several square kilometers. Arizona currently has 14 flux tower sites, primarily located in the southern part of the state (Upper San Pedro, Cienega Creek, and Tucson basins), with additional sites in northern regions (Coconino Plateau and Verde River basins).

Comparisons with flux tower observations indicate that:

- Noah-MP and the NWM reproduce the seasonality and daily variability of ET reasonably well, except in areas that are not water-limited (e.g., riparian corridors and floodplains), where vegetation can access shallow groundwater.
- The SWAT model reasonably reproduces seasonal patterns of ET but does not provide accurate estimates of magnitudes.
- OpenET tends to overestimate ET for much of the year, particularly in spring and fall.
- MODIS ET generally underestimates ET, except during winter.
- ECOSTRESS is most accurate over seasonal time scales (Lewis and Sankey, 2025).

MODIS and OpenET datasets were subsequently integrated by the ATUR team to produce a bias-corrected statewide seasonal ET product at a 1 km scale over a 20-year period. This product constrains the satellite ET data using a Budyko curve, which describes the relationship between the evaporation ratio (long-term mean actual ET divided by long-term mean precipitation, P) and aridity index (potential ET divided by P). These ratios were derived from flux tower data. This approach produced a gridded estimate of long-term mean annual ET, which was then temporally disaggregated using the repeated satellite measurements.

As shown in Figure 2.6, annual ET rates are highest and, in some locations, exceed precipitation in areas with persistent water availability, including riparian corridors, irrigated cropland, urban landscapes, and open water. As expected, ET is constrained by precipitation in most other land cover types. In lower-elevation desert regions, nearly all precipitation is returned to the atmosphere through ET; however, because total precipitation is low, absolute ET volumes remain relatively small. In contrast, higher-elevation regions such as the Mogollon Rim receive greater precipitation and therefore exhibit higher total ET volumes, even though ET represents a smaller fraction of annual precipitation. Due to their large spatial extent, these highlands account for the greatest overall ET volumes statewide (excluding localized high ET over water bodies and irrigated areas).

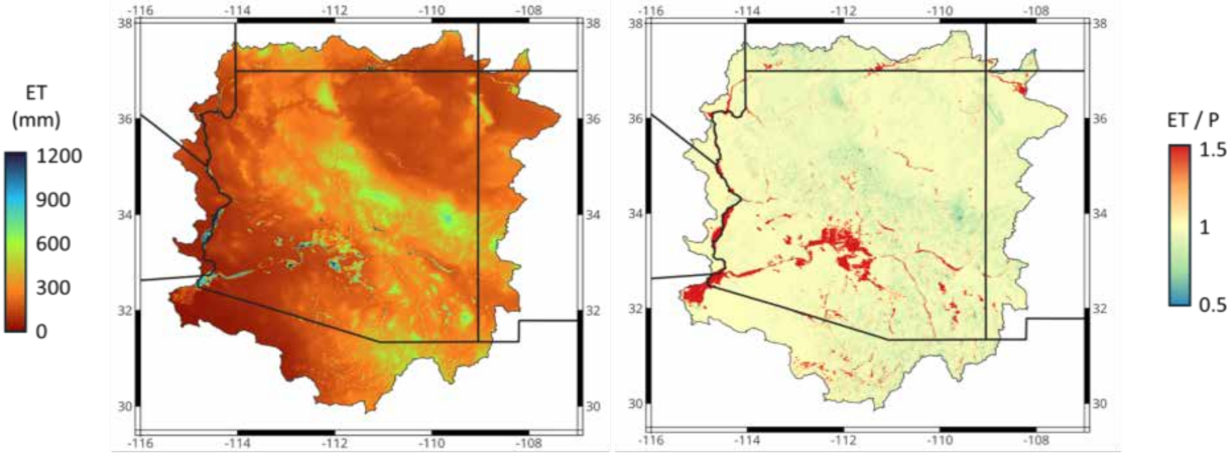


Figure 2.6. Average annual ET (left panel) and ET/P (right panel) from the bias corrected ET product developed by ATUR researchers by integrating multiple remote sensing products and applying aridity constraints via the Budyko framework (Source: Broxton et al., in press).

There are benefits of high ET. ET supports crop and vegetation productivity, cools land and water surfaces for people and wildlife, and supports fish and aquatic life where there is surface water. ET is a major component in the broader hydrologic and biogeochemical cycling of matter and energy. In theory, higher use of water by vegetation as opposed to direct evaporation from soil and water would equate with more biological productivity at the lower elevations. Removal of vegetation does decrease transpiration, but it may increase the evaporative component, so it has to be done carefully in order to avoid negative consequences.

Quantifying Groundwater Recharge across Arizona

Key Message 2.3:
Natural groundwater recharge represents a small fraction of Arizona's water budget, accounting for less than 3% of average annual precipitation statewide. However, recharge varies substantially across the state's groundwater basins, ranging from less than 1% to more than 10% of annual precipitation in individual basins.

Because evapotranspiration dominates the statewide water balance, only a small fraction of annual precipitation contributes to natural groundwater recharge. Using Noah-MP and National Water Model (NWM) simulations at 4- and 1-km resolution, the ATUR team estimated mean annual recharge across Arizona during the historical period. Statewide, recharge accounts for approximately 3% of annual precipitation.

At finer spatial scales, recharge exhibits substantial variability. In some basins, such as Gila Bend, recharge approaches zero as a percentage of annual precipitation, reflecting strong evaporative losses and limited infiltration. In contrast, in basins such as the Salt River, recharge can exceed 10% of annual precipitation, consistent with higher precipitation totals, mountainous terrain, and greater infiltration capacity (Figure 2.7).

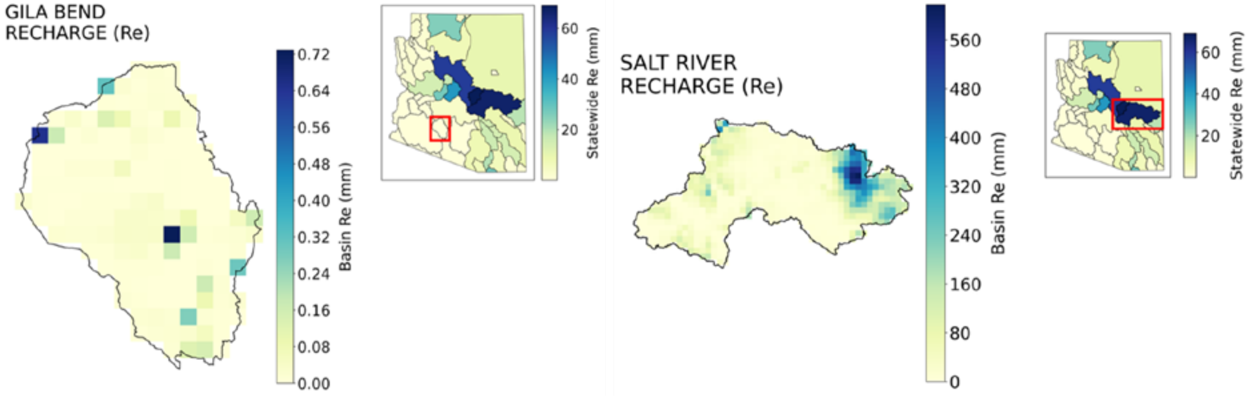


Figure 2.7. Comparison of mean annual recharge from Noah-MP modeling for the Gila Bend and Salt River groundwater basins (Source: A. Gupta, 2026; Figure Credit: Hinkley).

Outputs of both the NWM and Noah-MP model suggest that, across the state, the mean annual recharge is often the smallest component of the water balance, with a statewide average of less than 3% of the mean yearly precipitation. Higher percentages, up to 10.5%, are simulated in the Salt River groundwater basin, while negligible recharge occurs in southwestern Arizona, particularly in the Gila Bend basin.

Key Message 2.4:
Based on modeling results, groundwater recharge generally peaks in early spring in Arizona due to snowmelt in mountainous areas. However, recharge peaks later (May-June) on the Colorado Plateau.

The Noah-MP variables include near-surface air temperature, precipitation, recharge, top-layer soil moisture, and three components of evapotranspiration: transpiration, canopy interception loss, and soil evaporation. Using these monthly Noah-MP–derived values for the 1980–2020 period, we calculated long-term monthly means for Arizona's three major physiographic provinces, including the Colorado Plateau, Basin and Range, and Transition Zone. This province-based climatology provides a physically consistent foundation for evaluating temporal variability in groundwater-relevant hydrologic drivers and serves as the basis for ongoing assessments of groundwater basin trends within the ATUR hydroclimate framework. As shown in Figure 2.8, groundwater recharge rates averaged across Arizona exhibit a clear annual cycle, with a pronounced peak in late winter into spring, corresponding to winter precipitation and snowmelt from higher-elevation regions (Eastoe 2023, Chambless et al. 2023, Denver et al. 2025). This finding is directly influenced by higher temperatures during the summer monsoon, which lead to greater evaporative losses. Peak discharge is somewhat delayed along the Colorado Plateau relative to other basins due to snowmelt-derived runoff, which generally occurs later there because of lower temperatures and higher elevations. This pattern appears consistently across Noah-MP simulations forced by different precipitation datasets (AORC and CONUS404).

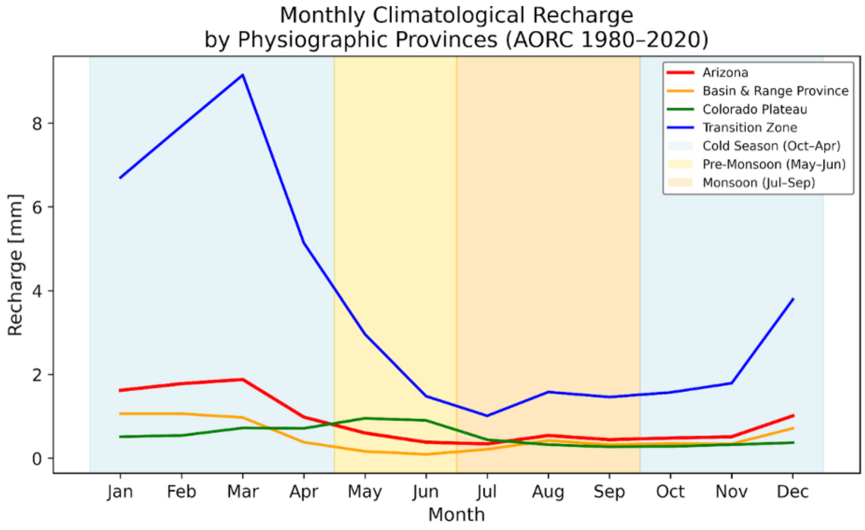


Figure 2.8. Average monthly recharge amounts derived from Noah-MP simulations forced with AORC data, shown as area-averaged volumes (depth in mm), for groundwater basins across the state of Arizona that have been aggregated into physiographic provinces and statewide levels to generate high-level insights into recharge timing and mechanisms (Source: A. Gupta, 2026; Figure Credit: Mohsenzadeh Karimi).

The Role of Precipitation Intensity in Recharge

Key Message 2.5:
With some exceptions, higher precipitation intensity increases the rate of groundwater recharge, especially during the summer; however, there is an optimum range of precipitation intensity for recharge because on-site recharge can be limited if a large proportion of the precipitation becomes surface runoff.

Precipitation amount and intensity are important parameters for understanding future trends in groundwater recharge. Few studies have looked at precipitation intensity in order to link them to recharge, but there is observational evidence in various basins in Arizona that recharge rates are significantly enhanced following major rainfall/flooding events. In the USDA Walnut Gulch Experimental Watershed (WGEW) near Tombstone, Arizona, over 70 years of continuous observations indicate that runoff and recharge only occur due to high-intensity thunderstorms during the monsoon and from the occasional tropical depression. Low intensity winter precipitation produces virtually no runoff in the WGEW (Goodrich et al., 2004). In this context, it is notable that both extreme precipitation events and drought intensity are expected to increase in frequency due to climate change. Modeling experiments using the Noah-MP land surface model indicate that high precipitation intensity resulted in an annual groundwater recharge rate of ~15 times that of low precipitation intensity, with an increased rate of recharge most pronounced in mountainous regions (Qiu et al., 2025). Consistent with many other studies over other regions (Asoka et al., 2018; Jasechko & Taylor, 2015; Owor et al., 2009; Thomas et al., 2016), high intensity precipitation leads to more groundwater recharge because it is associated with increased infiltration and percolation that moves water past the root zone before it can be evaporated or transpired. Under the same or similar volumes of total annual precipitation, higher precipitation intensity can lead to significantly more annual groundwater recharge in the study area (Qiu et al., 2025).

Our modeling results also suggest that there is a threshold precipitation rate (P) to trigger groundwater recharge (Re), which is the evapotranspiration (ET) rate; recharge then increases linearly with the excess of P over ET until surface runoff begins. Therefore, there exists an optimum range of precipitation intensity for recharge because recharge is limited by surface runoff occurrence at higher precipitation rates. These findings are consistent across soil and vegetation types, although ponding does increase ET if soils are less permeable or surface sealing occurs when rain hits dry, clay soils. This ATUR study provides complementary evidence from regional hydrological modeling and, importantly, an explanation of how underlying mechanisms such as precipitation intensity affect groundwater recharge by modulating ET (see Figure 2.9).

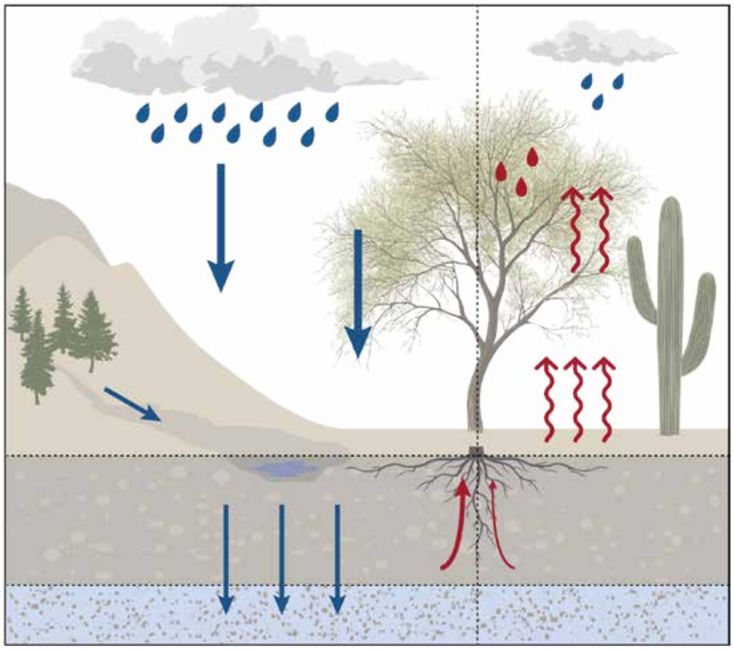


Figure 2.9. With higher intensity precipitation (left side), more rain is able to penetrate through tree canopy cover. This leads to a higher percentage of rain that reaches the ground, facilitating ponding and infiltration, often collecting in riparian areas. More water percolates past the root zone, allowing for greater potential groundwater recharge (if there is not a thick vadose zone between the root zone and the water table) (Walvoord et al, 2002 and 2002a). However, with higher intensity rain, there is also more water that reaches the root zone, leading to greater transpiration from vegetation. With lighter precipitation (right side), more water is trapped in the canopy layer, which leads to more direct evaporation. Additionally, light rainfall does not percolate as deeply, so a larger percentage of precipitation evaporates from the soil and root zones. (Source: Qiu et al., 2025; Figure Credit: Howe)

The Role of Groundwater-Supported Base Flow in Supporting Surface Water

Key Message 2.6:
Base flow, or the portion of streamflow sustained by groundwater discharge, accounts for approximately 32% of average annual streamflow in Arizona, with substantial variation across the state. Tracking changes in the base flow component of stream flow over time can help water managers understand how changes in climate are affecting groundwater contributions to streamflow and is a particularly useful tool for regions with limited direct groundwater monitoring.

The groundwater-fed component of streamflow sustained between precipitation events, known as base flow, plays a central role in maintaining perennial and seasonal flows in Arizona's rivers. As much of Arizona's runoff is episodic and ET rates are high, base flow often represents the most reliable source of surface water during extended dry periods. Using observed long-term records (1991-2020) coupled with machine learning (ML) techniques to extrapolate to ungauged basins, the ATUR team determined that groundwater-derived base flow contributes approximately 32% of statewide streamflow (on average annually), though contributions vary substantially with geology, basin structure, and climate (Mroczek et al., 2025). These spatial patterns mirror global findings that hydrologic setting, soil permeability, and aridity strongly govern the magnitude of base flow (Beck et al., 2013; Santhi et al., 2008).

Due to variability in flow volumes, long-term base flow is often measured as a Base-flow Index (BFI), a normalized measure of groundwater contribution defined as the ratio of the long-term mean base-flow volume to the long-term total streamflow volume. Areas such as the Grand Canyon, the Mogollon Rim, and spring-fed headwaters exhibit high BFI values, reflecting strong connectivity between aquifers and stream channels. In contrast, basins underlain by low-yield aquifers, such as portions of the Defiance Plateau in Apache County, show consistently low BFI values, highlighting limited groundwater contributions to streamflow. Integrating observed base flow patterns provides a more complete picture of where groundwater contributions are strongest, how they are changing, and where recharge-focused management could have the greatest impact. Wet-dry mapping to measure the wetted length of channel (base flows) during the pre-monsoon season is one way to measure changes over time; it has been instrumental in determining near stream groundwater levels, and the closely associated riparian health of streamside habitats (Turner and Richter, 2011).

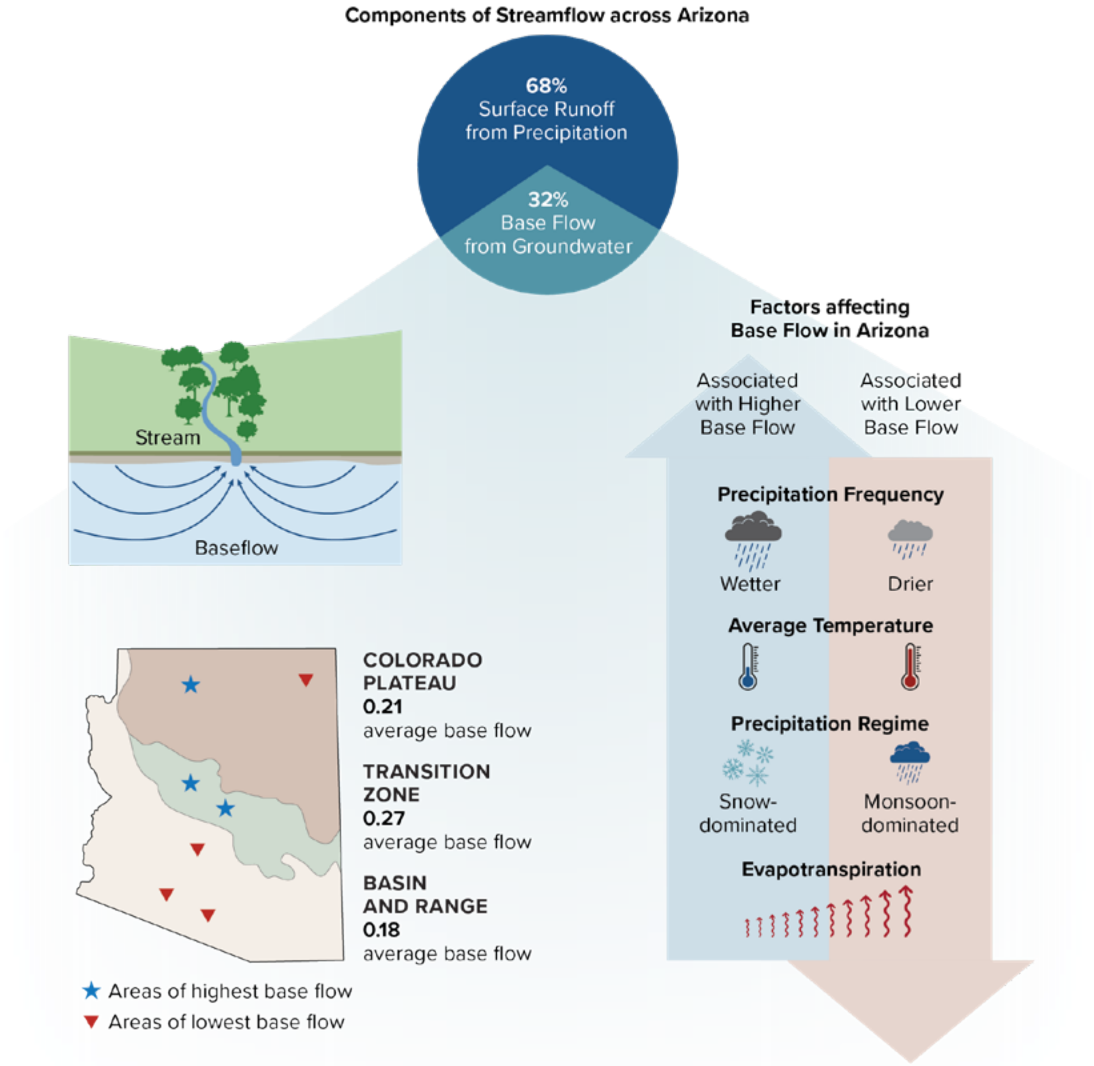


Figure 2.10. Base flow is the portion of streamflow derived from groundwater, reflecting the interactions between recharge and surface water. It acts as a natural buffer that sustains streamflow during dry periods and serves as a useful indicator of recharge at the local scale. The contribution of base flow to total stream flows is declining across many of Arizona's watersheds. (Source: Mroczek et al., 2025; Figure Credit: Howe)

Trends observed across Arizona's gauged network show that base flow is a sensitive indicator of shifting recharge conditions and climate stress. Analyses of more than 200 stream gauges indicate that BFI and base flow volume trends most frequently align with precipitation trends, reinforcing the central role of seasonal moisture inputs in sustaining groundwater discharge. These findings are consistent with national-scale studies showing that warming temperatures, declining snowpack, and reduced infiltration are contributing to widespread base-flow declines in arid and semi-arid regions (Ficklin et al., 2016; Ayers et al., 2022). In Arizona, base flow typically peaks in winter and early spring when snowmelt occurs in upland watersheds before re-emerging as sustained low flows in many dryland basins. Such declines are especially pronounced in warm-dry and monsoon-dominated basins, where rising temperature and evaporative demand amplify hydrologic stress. However, it should be noted that alluvial floodplains have significant capacity to buffer seasonal ET demand as long as the input (storm flows) are big enough. For example, base flows in the Upper San Pedro River were elevated for about a year after Hurricane Odile in September of 2014 (The Nature Conservancy, 2025).

Because stream gauges continuously record low-flow periods, base-flow metrics derived from observations and ML techniques offer an indirect but powerful means for diagnosing basin-scale groundwater conditions, assessing climate sensitivity, and identifying zones where recharge is naturally concentrated. This is especially important in Arizona, where headwater regions, mountain fronts, and spring complexes serve as critical recharge zones that sustain dry-season flows. Regional studies of southwestern rivers show that warming-driven declines in base flow threaten ecological function, water supply reliability, and long-term aquifer sustainability (Woodhouse & Udall, 2021).

Connections Between Climate Change and Water Supply Reliability

Key Message 2.7:
ATUR model estimates show that climatic factors can explain much of Arizona's terrestrial water storage (TWS) declines since 2000 (2000–2020). Our model-based TWS depletions are consistent with GRACE satellite gravity-based observations (which incorporate all reductions in water supplies, including both groundwater pumping and climate-driven depletion).

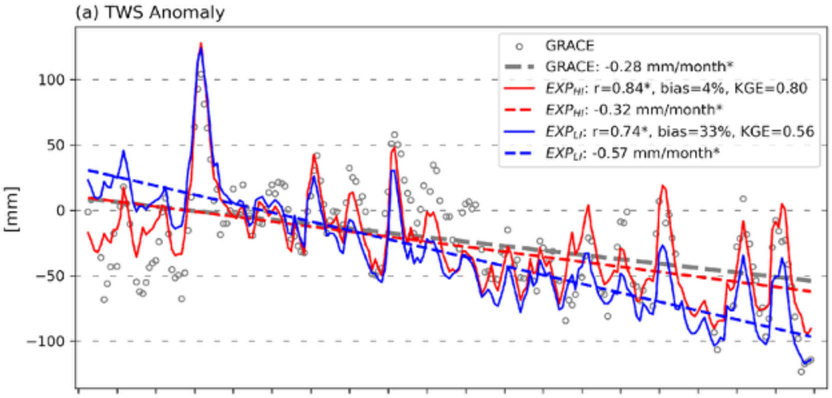
A major motivation for this project is promoting water supply reliability in the context of increasing temperatures. Observations from the GRACE satellite provide a way to verify the overall trends that have been observed over the last 20 years and appear in our modelled water balances.

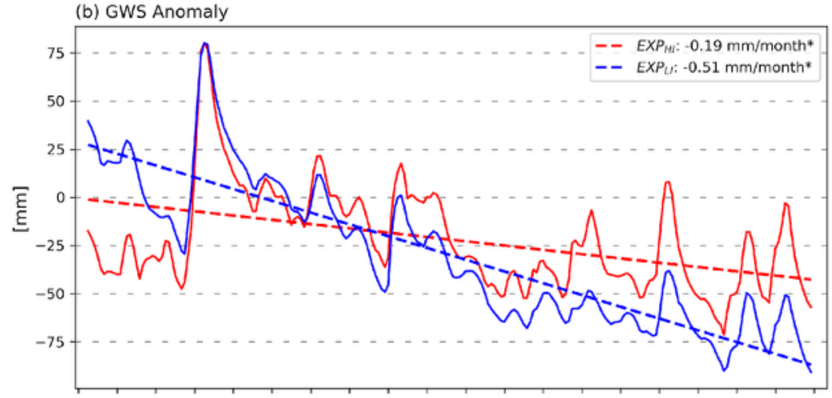
Noah-MP simulations forced with three different precipitation datasets (AORC, CONUS404, and the Integrated Multi-satellitE Retrievals for GPM or IMERG) consistently reproduce a declining trend in Arizona's terrestrial water storage (TWS) similar to that observed by the GRACE satellite but at a different declining rate (Figure 2.11). Terrestrial water storage is comprised of both groundwater storage (aquifers) and surface water storage (reservoirs, rivers, snow water equivalent, soil moisture, etc.). Although the magnitude of the trend varies across forcing datasets, all simulations capture the long-term TWS decline. Importantly, the Noah-MP model does not include human water use such as groundwater pumping or irrigation. The fact that the model—driven only by climate—still reproduces the statewide decline in TWS suggests that: 1) climate-driven factors (e.g., warming, changes in precipitation seasonality) play a significant role in Arizona's long-term TWS decline; and 2) local groundwater pumping may dominate storage impacts in specific areas, but climate impacts are likely the primary contributor statewide. Figure 2.11 shows the results of Noah-MP modeling experiments under high and low precipitation scenarios for (a) change in terrestrial water storage (TWS) compared with GRACE satellite data, (b) change in groundwater storage (GWS), and (c) change in surface water storage (SWS) integrated over all the HUC8 basins in Arizona.

In the model, GWS is the water stored in the saturated zone, whereas SWS includes the water stored in the unsaturated zone, SWE, plant water storage, canopy-intercepted water, and surface ponded water. The modeled anomalies are then calculated as the deviation from the temporal mean from 2004–2010, following the procedure of GRACE. The modeling results suggest that 1) the high precipitation dataset (CONUS404) produces a declining trend in total TWS closer to that of GRACE, indicating that precipitation products/inputs with higher precipitation rates are more likely to be accurate, 2) the low precipitation dataset (IMERG) produces a faster declining rate in GWS (-0.51 mm/month) due to the lower groundwater recharge rate (see **KM** **2.5** and 3), the long-term change in groundwater storage (-0.19 mm/month for the high precipitation dataset and -0.51 mm/month for the low precipitation dataset) is the biggest contributor to that in the total TWS. Note that partitioning of TWS into SWS and GWS in the model involves changes in the thickness of the unsaturated/saturated zones due to changes in groundwater level. Therefore, the faster declining rate in GWS (Figure 2.11b) resulting from the low precipitation rate is caused by its faster drop in groundwater level, while the SWS declines at a slower rate (than the high precipitation dataset) because of the thickening of its unsaturated zone.

The sensitivity of the modeled TWS change and its components to precipitation intensity highlights the need for improving the accuracy of precipitation intensity in precipitation products. The use of in-situ (e.g., rain gauges) precipitation data to bias adjust precipitation products is valuable, but some products, such as IMERG, perform bias adjustment at the monthly scale, which may not be as effective as adjustment at shorter time scales (e.g., daily and hourly).

The ATUR team developed projected changes in precipitation (P) and temperature (T) for all groundwater basins as well as associated changes in ET, SR, and Re using climate scenario Shared Socioeconomic Pathway (SSP) 3-7.0 (high greenhouse gas emissions, CO2 emissions double by 2100) from the Intergovernmental Panel on Climate Change (IPCC). This work was completed for the entire Colorado River watershed and involved significant bias correction efforts to ensure the most accurate projections of future conditions for use in the groundwater basin summaries (see Appendix A).





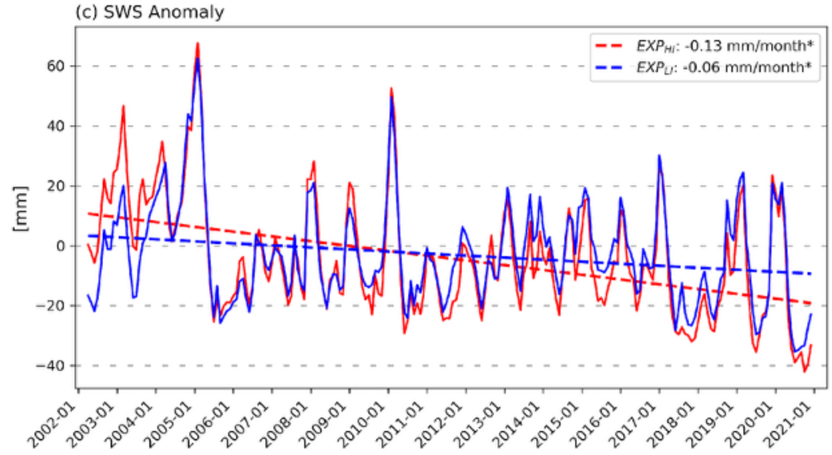


Figure 2.11. (a) Time series of monthly terrestrial water storage (TWS) anomaly averaged over Arizona HUC 8 basins from Gravity Recovery and Climate Experiment (GRACE, dots) and the two experiments (solid lines: EXPHI using CONUS404 while EXPLI using IMERG). (b)–(c) Same as (a), but for groundwater storage (GWS) anomaly and surface water storage (SWS) anomaly. Dashed lines represent the linear trend calculated using the least square method. Correlation coefficient (r), relative bias (bias), and Kling-Gupta Efficiency (KGE) are also shown in (a). Asterisks (*) indicate statistical significance at the 95% confidence level based on the student's t-test. (Source: Qiu, 2025)

Key Message 2.8:
Ensemble modeling of Arizona's water cycle under emissions scenario (SSP 3-7.0) projects robust and continuing temperature increases, alongside decreasing runoff and groundwater recharge, driven by rising evaporative demand and precipitation declines concentrated in the state's high-elevation water source areas.

We completed 14 ensemble runs with the Noah-MP land surface model across Arizona over the period 1981–2099, driven by dynamically downscaled outputs from 14 global climate models at 9-km resolution. The future socio-economic scenario selected, Shared Socioeconomic Pathway (SSP) 3-7.0, is considered an intermediate-high emissions scenario, and is the most commonly used scenario in recent Intergovernmental Panel on Climate Change and US climate modeling efforts. Statewide annual precipitation shows no statistically significant trend over this period (Fig. 1a); however, this area-averaged result masks important spatial heterogeneity, as discussed below. In contrast, surface air temperature is projected to increase at a statistically significant rate of 0.05 °C/year over 1981–2099 (Fig. 2.12b). It should be noted that the reason 14 different models were used to generate an ensemble projection is to overcome the substantial differences that exist among the 14 forcing datasets, particularly for precipitation (Fig. 2.12a). Furthermore, while linear trends are reported here for clarity, the rate of change is likely to accelerate in the latter half of the century, and these slopes should be interpreted as long-term averages rather than uniform rates.

Although an increase in fall season precipitation is anticipated in most parts of the state (related to a projected increase in extreme events associated with hurricane and tropical cyclone activity), higher temperatures will increase evaporative demand. The anticipated reduction in average winter precipitation at high elevations is expected to decrease runoff and recharge.

At the statewide scale, the interannual variation of evapotranspiration (ET) closely tracks that of precipitation (Fig. 2.13a), consistent with the water-limited regime characteristic of semi-arid environments like Arizona, where atmospheric moisture supply, rather than energy availability, is the primary constraint on ET. Both annual runoff and groundwater recharge are projected to decrease by approximately 0.05 and 0.07 mm/yr, respectively (Fig. 2.13b and 2.13c), driven by increasing evaporative demand under rising temperatures even in the absence of a significant precipitation trend.

Spatial analysis of two future periods, 2021–2060 and 2061–2099, relative to the baseline period of 1981–2020, reveals more nuanced patterns. Results for 2061–2099, when changes are projected to be most pronounced, indicate substantial decreases in annual precipitation over high-elevation areas (Fig. 2.14c). These high-elevation zones, such as the Mogollon Rim and White Mountains, function as Arizona's primary water sources and therefore dominate the area-averaged hydrological trends described above. The apparent contradiction between a statistically insignificant statewide precipitation trend and significant regional decreases reflects the state's diverse topography.

Projected changes in annual ET are spatially complex. Across most high-elevation areas, reduced precipitation drives a corresponding decrease in ET, consistent with the water-limited regime noted above. *However, a subset of mountainous areas is projected to experience increased ET (Fig. 2.15c), potentially attributable to shifts in snowmelt timing, which can alter the seasonal distribution of moisture availability*. Runoff and recharge are projected to decrease across the high-baseline areas (Fig. 2.16c and 2.17c), consistent with and reinforcing the area-averaged decreasing trends, with implications for water resource planning across the region.

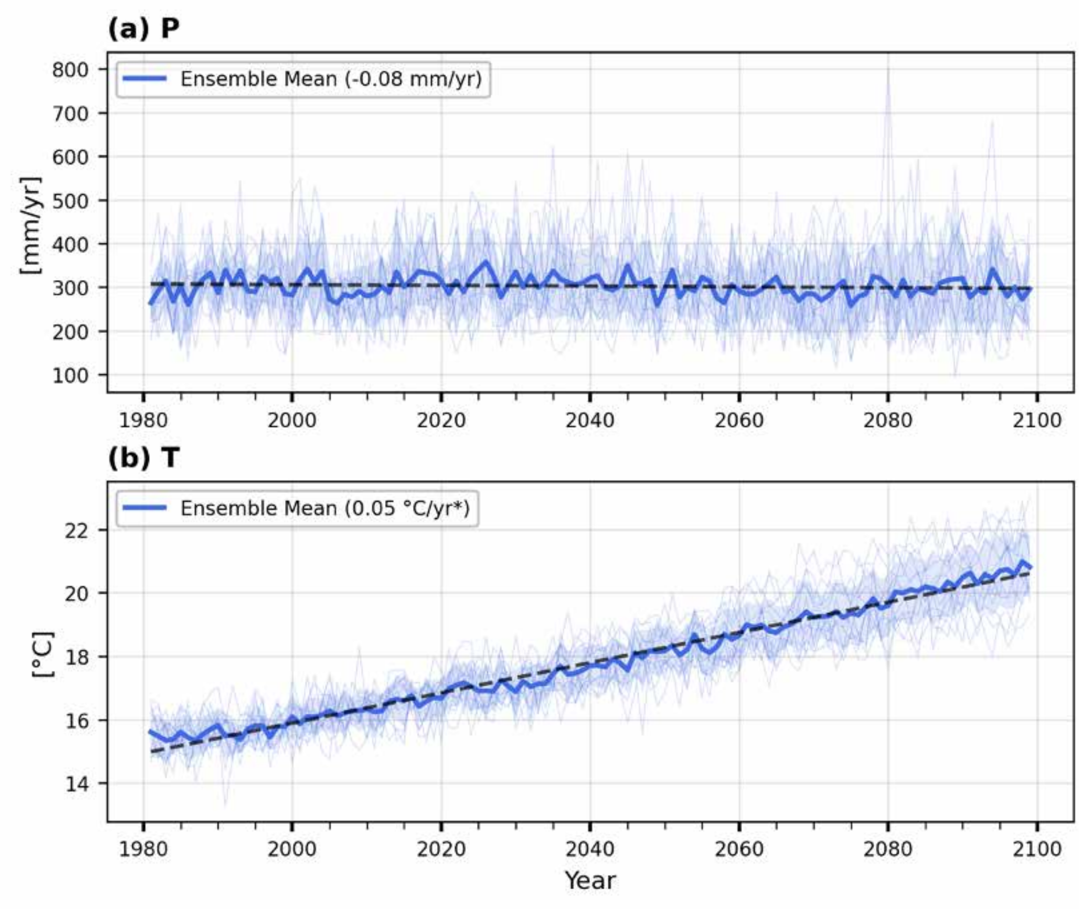


Figure 2.12. Annual (a) precipitation (P) and (b) surface air temperature (T) averaged over the state of Arizona over 1981–2099. Thick blue solid line: the ensemble mean of the 14 Noah-MP runs driven by downscaled results of different global climate models. Thin blue solid line: results of each run. Red solid line: results of the run driven by downscaled results of the CESM2 GCM. Dashed black line: the linear trend of the ensemble mean. *: the linear trend is significant at 95% confidence level using the Student's t-test. (Source: Qiu et al., 2026, in prep.)

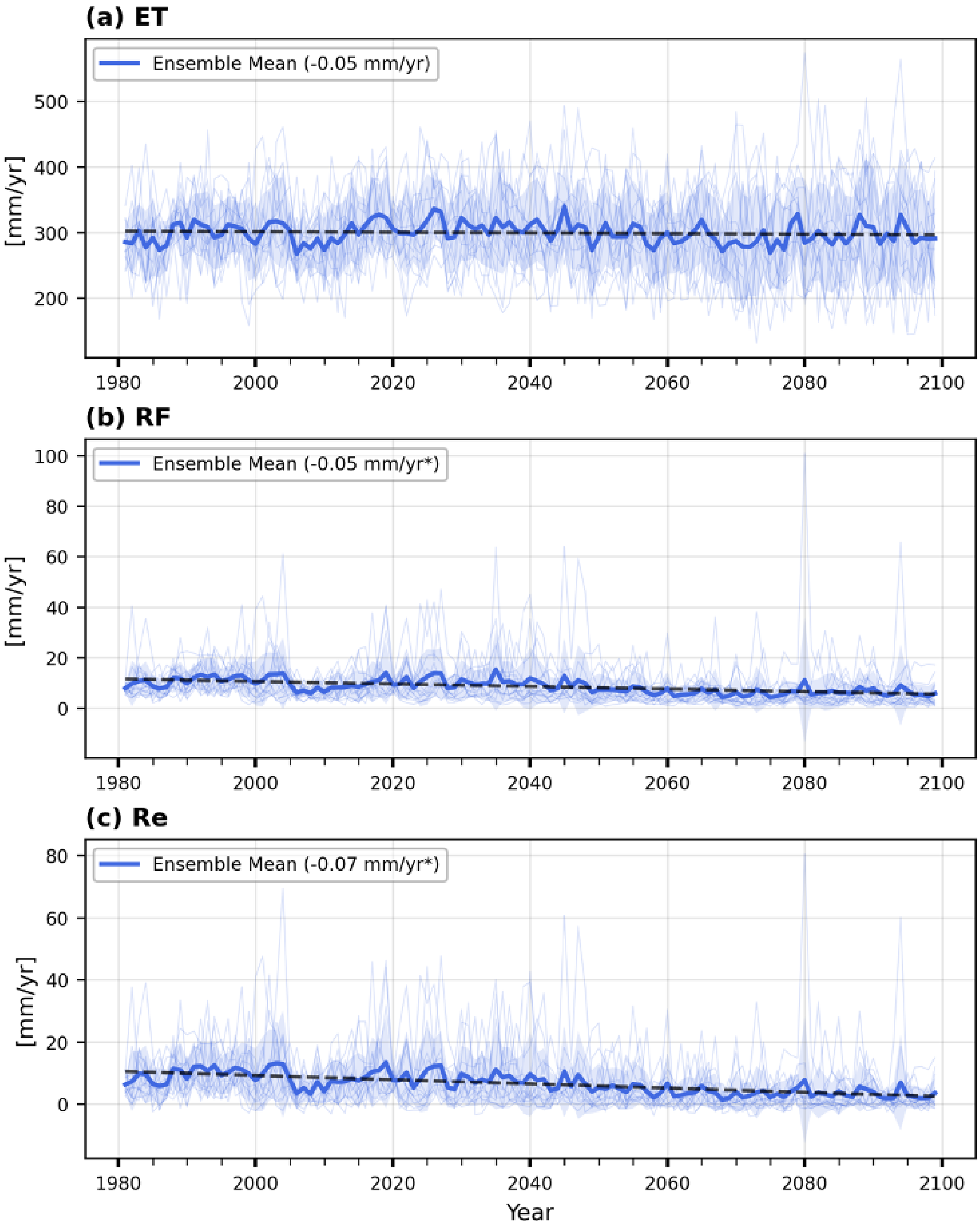


Figure 2.13. Same as Figure. 2.17, but for (a) evapotranspiration (ET), (b) runoff (R), and (c) recharge (Re). (Source: Qiu et al., 2026, in prep)

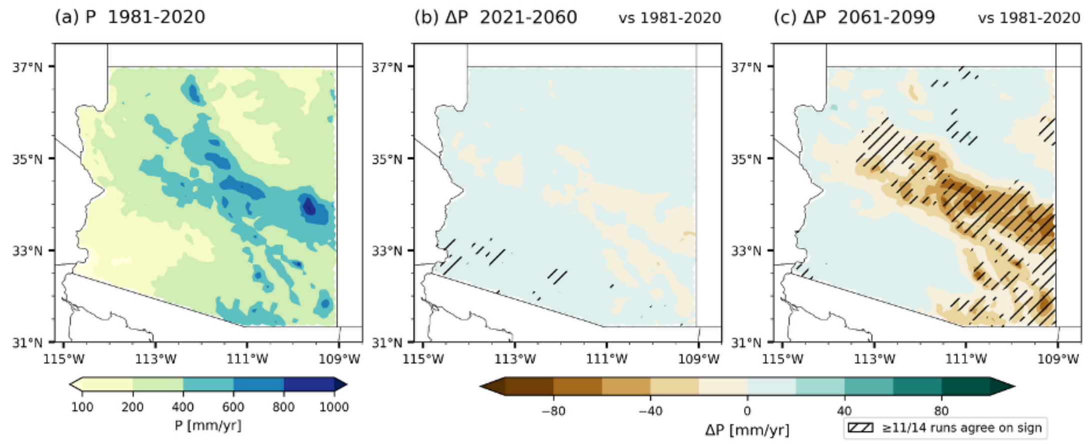


Figure 2.14. (a) Time-averaged annual precipitation (P) in Arizona over the baseline period (1981–2020). Changes in annual precipitation (P) over 2021–2060 (b) and 2061–2099 (c) relative to the baseline period. The hatched areas indicate that at least 11 of the 14 Noah-MP runs agree on the sign of change. (Source: Qiu et al., 2026, in prep)

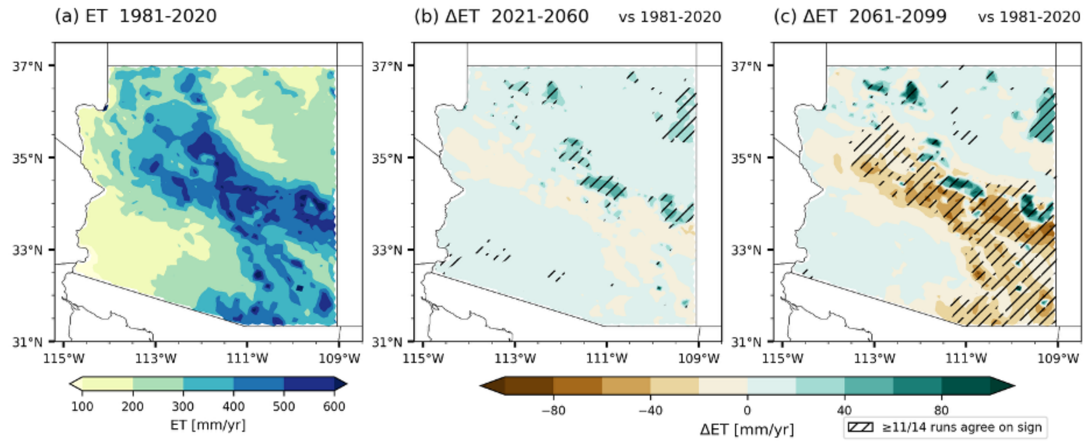


Figure 2.15. Same as Figure 2.19, but for evapotranspiration (ET). Note that reductions in future ET are significant across most but not all of the Mogollon Rim. (Source: Qiu et al., 2026, in prep)

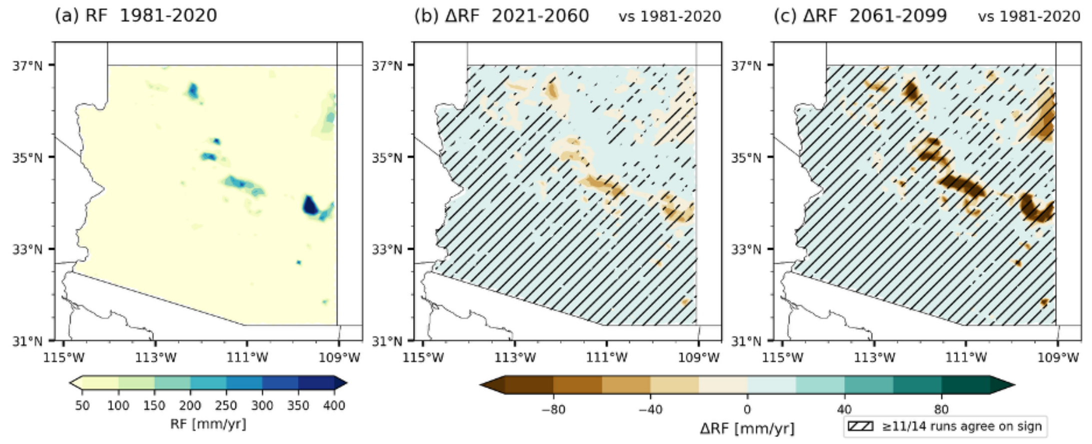


Figure 2.16. Same as Figure 2.19, but for runoff (R). (Source: Qiu et al., 2026, in prep)

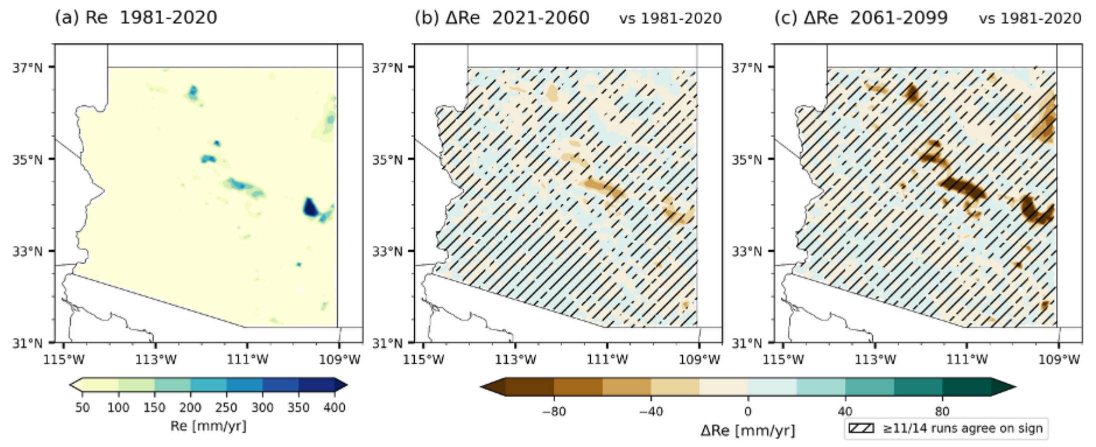


Figure 2.17. Same as Figure 2.19, but for recharge (Re). (Source: Qiu et al., 2026, in prep)

Preliminary findings of ATUR research (Qiu, in press) include evidence that location of the polar jet stream may be a significant driver of future climate, particularly during the springtime. To understand the effect of jet stream location on the hydrologic cycle, the latitude of the jet core (where the jet stream is the strongest) was calculated over the ~40-year period of 1982–2023. The analyses show a significant northward shift of the jet core in March over the past four decades. The five highest jet latitude years in March (where the jet core occurs significantly farther north than average) all occur post-2000, coinciding with the current multi-decadal drought. During the five highest jet latitude years, less precipitation (-3.61 mm) occurs on average in most areas of the Colorado River Basin. Associated with these changes, there is a pattern of increased wetness in the Pacific Northwest and drying in the Upper Colorado River Basin. For the same five high jet latitude (HJL) years in the historical record, temperature is higher (+2.06 degrees C) than average throughout the Western US. Due to less precipitation and warmer temperatures, there is less accumulation of snow water equivalent (SWE) during March (an average of –7.65 mm) in the Western US during these high jet years. This represents a 57.2% decrease in areas of net SWE gain across the Western US in HJL years compared to the climatology of 1982–2023. The greatest losses in net SWE occur in the Upper Colorado River Basin in the highest jet latitude years.

Projections of future hydroclimate conditions from 2070–2100 show a similar pattern of precipitation to the trends observed in the historical period, with annual precipitation increasing in the northern US latitudes and declines in precipitation in the southwestern US. Our team has linked these projected changes to the continued northerly shift of the polar jet core. This shift will likely continue to have a significant negative impact on Colorado Basin water supplies over time. Increases in average global temperatures and in temperatures across the Southwest are anticipated by all global climate models (GCMs) evaluated.

Anomalies in Precipitation, Temperature, and SWE Accumulation in High Jet Latitude (HJL) Years

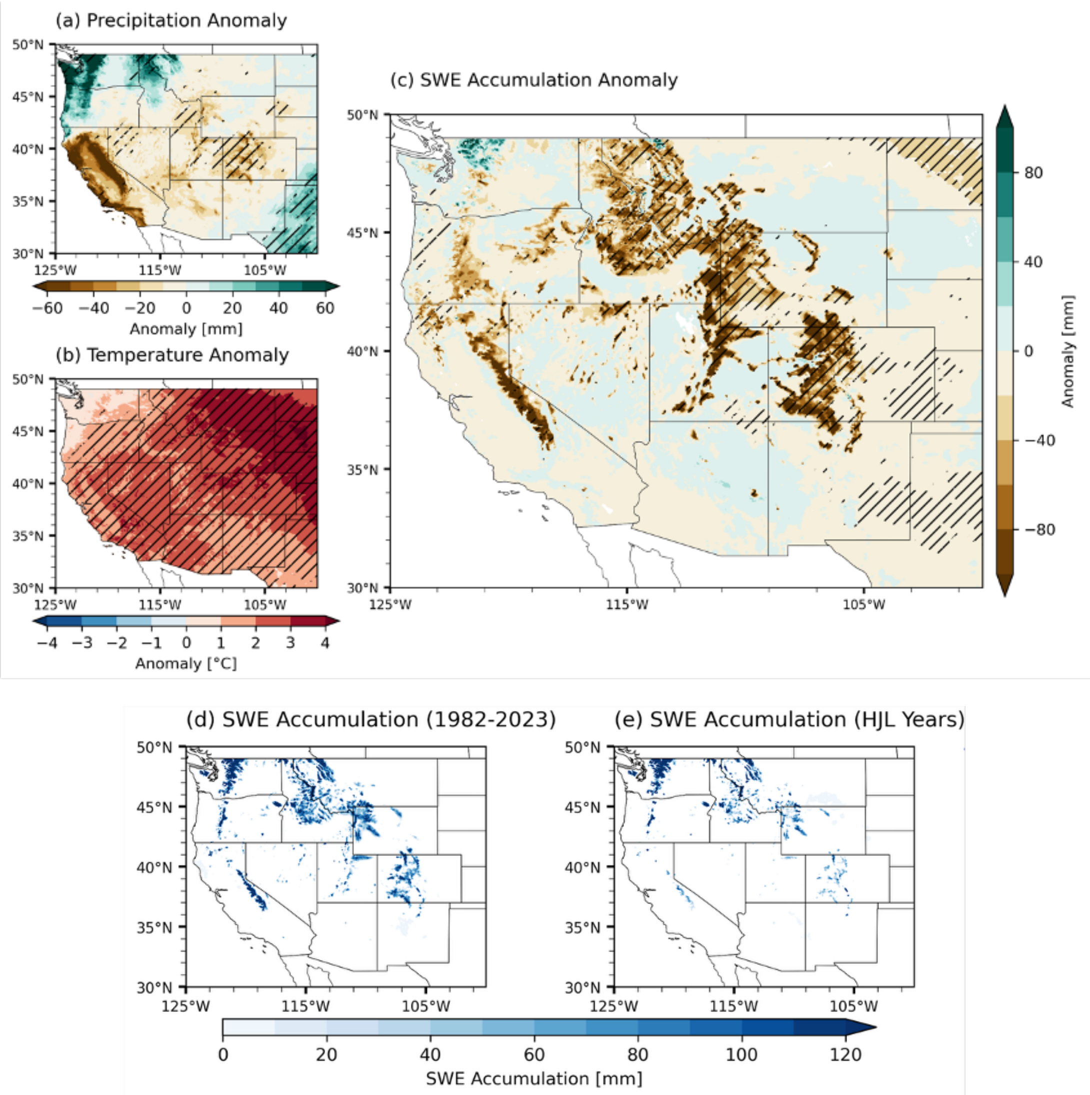


Figure 2.18. Anomalies in March (a) precipitation (-3.61 mm on average) (b) temperature (+2.06 deg. C on average), and (c) SWE accumulation (-7.65 mm on average) during the five highest jet latitude (HJL) years relative to 1982–2023. (d) Time-averaged March SWE accumulation (only showing the positive values) during 1982–2023, and (e) the five HJL years, revealing a 57.2% decrease in areas of net SWE gain in HJL years compared to the climatology of 1982–2023. (Source: Qiu, et al., in prep.)

Connections between Vegetation Change and Changes in the Hydrologic Cycle

Key Message 2.9:
Vegetation change alters the hydrologic cycle by modifying evapotranspiration and runoff, with stronger effects on precipitation partitioning at higher elevations. In the future climate–land cover scenario tested, most projected hydrologic changes are driven by climate, while vegetation shifts produce localized impacts, particularly at high elevation.

In Arizona's water-limited environments, climate change and vegetation change influence the water balance in fundamentally different but interacting ways. Climate change primarily alters precipitation amount, storm intensity, snowpack dynamics, and atmospheric evaporative demand (Seager et al., 2007; Jardine et al., 2013; IPCC, 2022). Rising temperatures and increasing vapor pressure deficit are intensifying atmospheric drying, reducing snow-derived water storage in upland systems, and increasing ET across the region (Udall & Overpeck, 2017; Williams et al., 2020). By contrast, vegetation change influences how the water is partitioned across the landscape by modifying interception, rooting depth, and the redistribution of water through evapotranspiration and runoff pathways (Scott et al., 2008; Wilcox et al., 2012).

Over the past century, Arizona ecosystems have undergone widespread vegetation transitions. For example, desert grasslands have experienced extensive shrub encroachment (Browning et al., 2008; Browning et al., 2014; Archer et al., 2017), and pinyon–juniper woodlands have expanded into adjacent shrublands and grasslands across much of the Colorado Plateau and surrounding regions (Davis & Turner, 1986; Romme et al., 2009; Willliams et al, 2018). At higher elevations, ponderosa pine forests have shifted from historically open stands to denser conditions due to the absence of frequent fires, and in some areas have experienced large and/or intense wildfires that have caused extensive tree mortality (Covington & Moore, 1994; Fulé et al., 1997; Heinlein et al., 2005; Huffman et al., 2020). These changes are expected to continue in the context of future climate changes.

To better understand the hydrological consequences of combined climate and land cover change, the ATUR team conducted numerical experiments using the Noah-MP land surface model driven by five climate projections at 9 km spatial resolution under the SSP3-70 scenario (a relatively high impact scenario), which were designed to isolate the relative contributions of climate change and vegetation change. For each climate projection, two sets of simulations were conducted: one using historical land cover (based on USGS 1-km Global Land Cover) and another using a modified land cover scenario representing potential vegetation transitions under future climate conditions. We first determined areas that are currently occupied by forests and grasslands that are expected to get significantly warmer and drier (Sayre et al., 2025). We then mapped forested areas expected to transition to shrublands following severe disturbances such as wildfires (Guiterman et al., 2022) as well as grasslands expected to experience woody plant encroachment.

The ensemble mean of fourteen climate models, bias-corrected and assessed by the ATUR team, indicates general warming across the state with drying in many areas, especially in southeast Arizona and the Mogollon Rim (Figure 2.19). This results in overall reductions in modeled soil moisture and recharge. The climatic influence on ET was more complicated, reflecting differences in areas that are water limited (i.e. lowlands, where ET is constrained by precipitation) vs. areas that are not (i.e. highlands, where annual precipitation is greater than ET). In the water limited (lower elevation) regions, annual ET tends to track precipitation changes. In contrast, at higher elevations where water supply is not limiting, there are some areas where ET is expected to increase along with increases in atmospheric evaporative demand.

The climate change with modified land cover (vegetation change) simulations showed similar patterns to climate change only simulations (Figure 2.20a and b, d and e), indicating that most hydrological changes are strongly tied to climate change. However, there were some areas where modified vegetation had pronounced effects, especially at higher elevations (Figure 2.20c and 2.20f). For lower elevation grasslands and shrublands, vegetation change did not appear to have a large impact on the annual water balance because land cover changes do not tend to change climate-controlled limits on total ET (Huxman et al., 2005; Wilcox et al., 2012). At higher elevations, where shifts in canopy structure and snow-related processes can alter ET dynamics (Tatum et al., 2025), vegetation change had a much larger impact. There, land cover change (primarily from forests to shrublands) mitigated some of the increases in ET and decreases in soil moisture / recharge. The impact was even stronger for areas where high elevation grasslands were converted to shrublands as the combined land-cover/climate change simulation showed, relative to the present climate, a decrease in ET and an increase in modeled recharge (which represents water drainage past the modeled soil layers) in some of these areas.

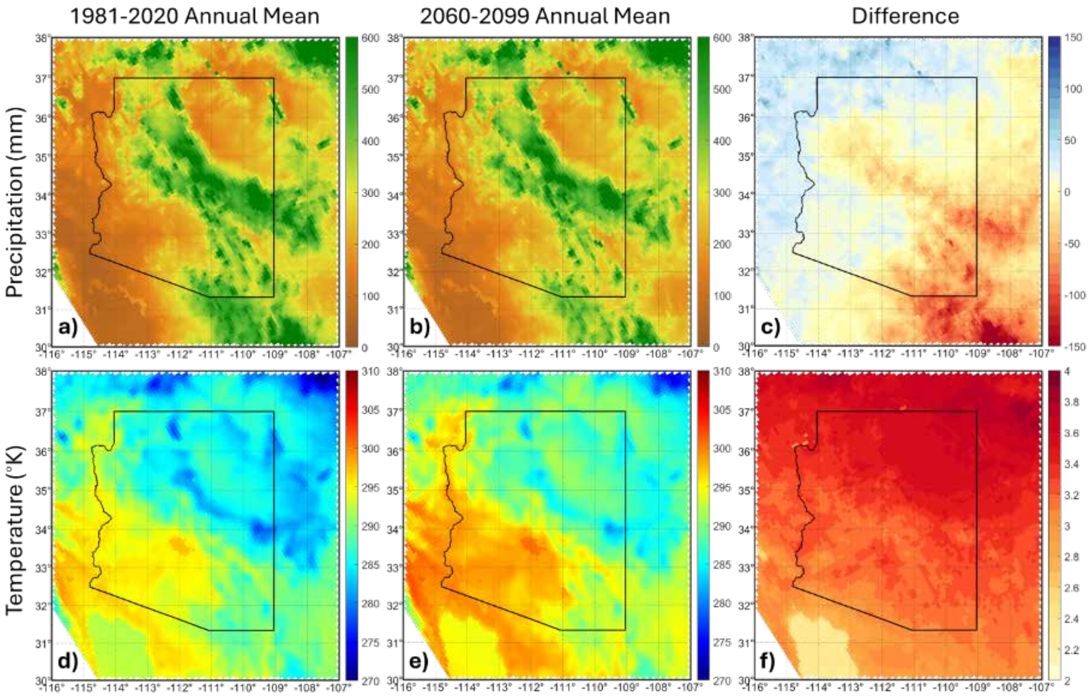


Figure 2.19. (a) 1981–2020 mean annual precipitation (mm), (b) 2060–2099 mean annual precipitation (mm), and (c) end of century precipitation difference (2060–2099 minus 1981–2020); (d) 1981-2020 mean annual temperature (K), (e) 2060–2099 mean annual temperature (K), and (d) end of century temperature difference (2060–2099 minus 1981–2020). (Source: Ensemble mean of CESM2, EC-EARTH3, GISS-E2-1-G, MPI-ESM1-2-HR, and UKESM1-0-LL; Figure Credit: Zhang)

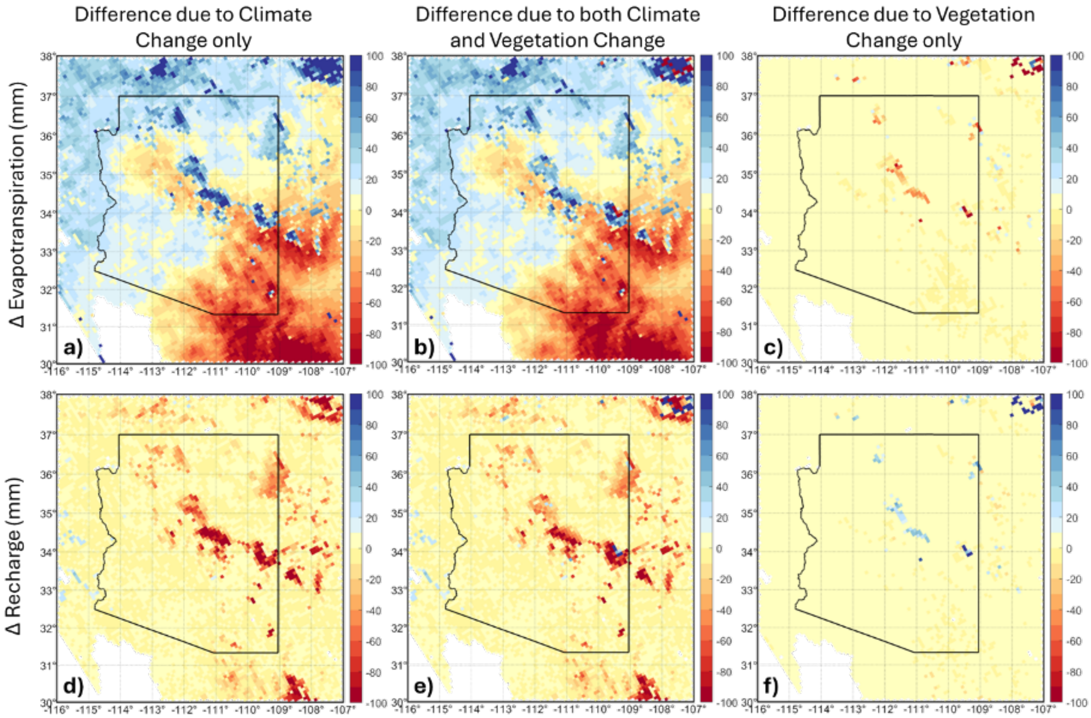


Figure 2.20. (a) Difference in annual average modeled ET (mm) due to climate change only, (b) due to both climate and vegetation changes, (c) due to vegetation change only; (d) difference in annual average modeled recharge (mm) due to climate change only, (e) due to both climate and vegetation changes, and (f) due to vegetation change only. Maps (a) and (c) show 2060–2099 minus 1981–2020 averages based on the simulation with current land cover, (b) and (d) show 2060-2099 (hypothetical land cover) minus 1981–2020 (current land cover) averages; (c) shows the difference between (a) and (b), and (f) shows the difference between (d) and (e). Note that all color bars range from -100 to 100 mm (for clarity) even though individual map pixels can fall outside this range. (Source: Ensemble mean of Noah-MP simulations driven by CESM2, EC-EARTH3, GISS-E2-1-G, MPI-ESM1-2-HR, and UKESM1-0-LL; Figure Credit: Zhang)

SECTION 3

RECHARGE ACROSS DIVERSE LANDSCAPES

A key focus of the ATUR project is the identification of strategies to capture and recharge water across the diverse landscapes of Arizona. There is a wide array of strategies available (see Appendix F), some of which are common practice while others are not well-established or researched. Large-scale artificial recharge efforts, mostly constructed facilities, have been developed primarily within the Basin and Range province, but there are areas across the state that have recharge potential that warrant additional consideration. At low elevations, generally high aridity and evaporative demand limit the amount of water that can be captured and recharged. However, there are significant management opportunities to enhance recharge in mid- to high-elevation forests, mountain fronts, and riparian areas. There is an abundance of opportunities across the state to provide ecosystem benefits through enhancing infiltration and plant-available water.

The Basin and Range province is characterized by limited precipitation (concentrated primarily in high-elevation areas) and high potential evapotranspiration (PET) in the valleys, which restricts the amount of water that can be effectively captured and stored in the subsurface. Even during wet years, much of the precipitation is lost quickly to evaporation or taken up by vegetation before it can percolate into deeper soil layers or the groundwater aquifers. This moisture limitation has long constrained natural recharge processes (Scott et al. 2000; Seyfried et al. 2005). However, even in these drier areas, there are opportunities to provide ecosystem benefits through enhancing infiltration and plant-available water such as managing and collecting stormwater in basins and dry wells, in-channel structures, and diversion of sheet flows to favorable recharge locations.

Landscapes in mid- to high elevations present more promising recharge options. Higher elevation areas, including forested mountain blocks, receive substantially greater precipitation (Boos and Pascale 2021). If winter snowpack within forested areas melts slowly, it can create extended periods of infiltration (Markovich et al. 2019). Carefully designed forest thinning treatments to minimize evaporation and sublimation, forest-floor restoration to enhance infiltration, and strategic post-fire rehabilitation can help promote larger snowpacks, reduce overland flow, reduce wildfire risk, and improve soil structure, thereby increasing recharge potential in these upland areas (Simonit et al. 2015; Schenk et al. 2020; Broxton et al. 2025).

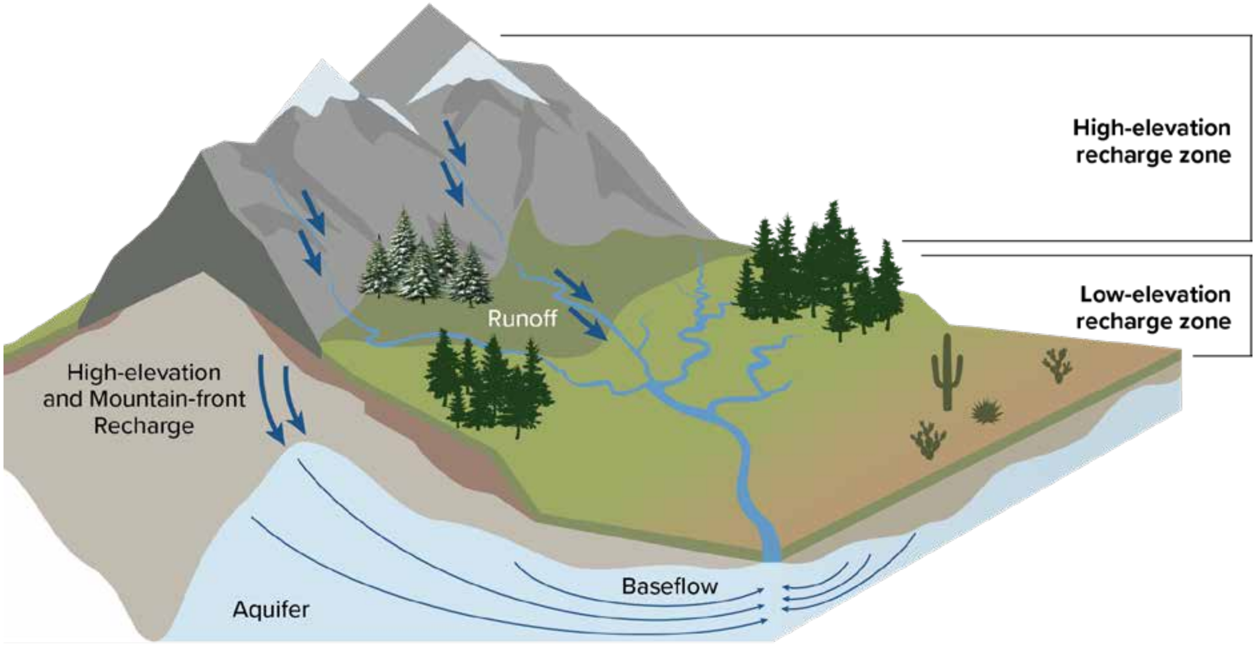


Figure 3.1. About 60% of annual precipitation falls as winter snow on the Colorado Plateau and Mogollon Rim. Cold conditions slow snowmelt, allowing deeper infiltration that sustains groundwater recharge into downstream base flow. Deeply infiltrated snowmelt emerges as increased base flow at lower elevations, which maintains base flow during dry periods and strengthens long-term water resilience. (Source: Baker, 2013; Figure Credit: Mohsenzadeh Karimi)

Mountain-front grasslands, which are often found between high-elevation forests and arid lowlands, also provide opportunities to enhance infiltration by reducing soil compaction, enhancing organic material in soils, managing grazing intensity, and slowing water flows in channels. Though it may be difficult to measure recharge outcomes, these treatments can increase infiltration, prolong soil moisture retention, and increase the likelihood that water percolates deeper rather than evaporating rapidly (see Groundwater Recharge and Environmental Enhancement Opportunities in Grasslands in Arizona).

Riparian corridors and ephemeral streams represent focal points where runoff naturally concentrates. By restoring floodplain connectivity, reducing channel incision, minimizing bank stabilization, and limiting invasive species, managers can potentially reduce ET and increase overbank flows which may promote recharge of shallow groundwater supplies (Webb and Leake 2006; Katz et al. 2009). Keeping riparian forests healthy and controlling excessive runoff from high-elevation areas are two of the most critical factors in this effort. Even where deep recharge potential remains limited, interventions across these ecosystems can yield substantial co-benefits by improving soil moisture availability, enhancing vegetation resilience, reducing erosion, and supporting wildlife habitat (Nichols and Polyakov 2019; Norman et al. 2022; Ossanna et al. 2024); (see “Guiding Principles for Enhancing Recharge and Habitat”).

Key Message 3.1:
Generally, the controlling factor for inducing recharge is the movement of water vertically, past the root zone. Saturated conditions at the ground surface (surface ponding) lead to much higher vertical water flux. The ponding duration required to initiate recharge depends on local conditions, and is challenging to predict and difficult to measure directly. There is a substantial decline in recharge feasibility in soils with greater than 20% clay content.

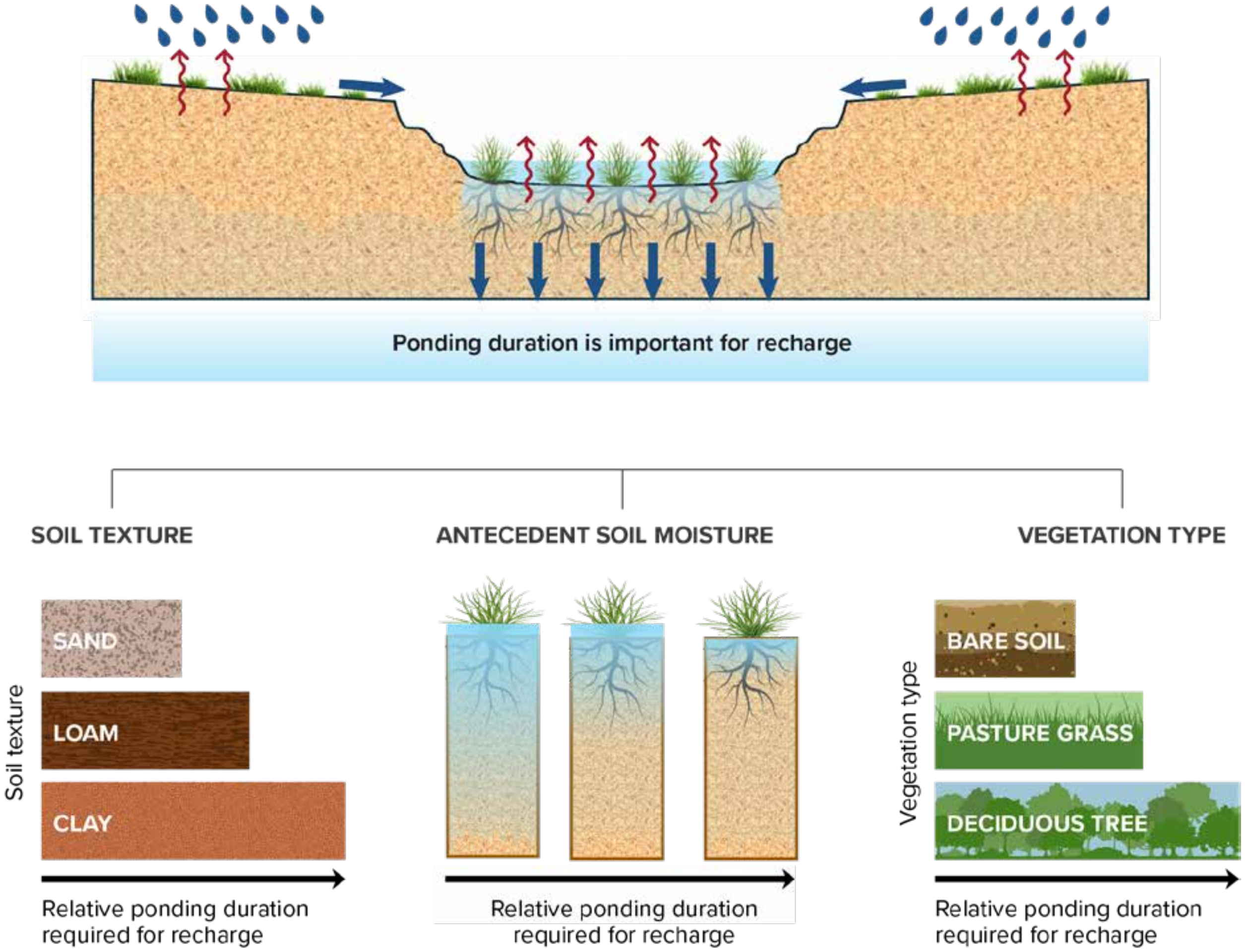


Figure 3.2. In Arizona, ponding at the soil surface is often required to overcome evaporation and transpiration losses in the upper soil layers and to generate recharge. The required ponding duration (length of time that water is on the soil surface) for recharge depends on 3 factors: (1) soil texture, (2) antecedent soil moisture (soil moisture prior to ponding), and (3) vegetation type and root depth. (Source: Strom, 2025; Figure Credit: Hinkley)

Ponding of water on the soil surface in natural depressions or detention basins as a result of intense precipitation events presents an opportunity for enhanced groundwater recharge in Arizona (Qiu et al., 2025), but site-specific conditions must be met for it to occur. Ponding of water alone does not ensure recharge; infiltrated water must overcome evaporation losses from the soil and plant root uptake and percolate beyond the near-surface (root) zone into the deeper subsurface, and then eventually reach the water table. The efficiency of infiltration and percolation depends on the site-specific interactions between soil texture, vegetation, and prior soil moisture conditions (antecedent soil moisture). For a given soil texture and vegetation type, wetter pre-ponding conditions tend to allow for quicker movement of water through the soil pores (hydraulic conductivity) and greater water available for vegetation, resulting in less infiltration required to initiate percolation past the root zone and into the deeper subsurface. As a result of these different variables, each site has distinct ponding duration requirements for generating recharge. Understanding these requirements for a proposed site can help inform management decisions, such as modification of vegetation or detention basin geometry, to ensure that the conditions support effective recharge to the extent possible.

A HYDRUS-1D model was developed by the ATUR team to explore the ponding duration required for effective recharge across different combinations of soil texture and vegetation. For the purposes of the model, effective recharge is defined as the condition in which 10% of the infiltrated water reaches a depth of 5 meters within 50 years after a ponding event. The model evaluates over 1,300 soil textures across four different representative vegetation cover types with increasing root depth and transpiration potential: bare soil, pasture grass, tomato (representing bush-like vegetation form), and deciduous trees. The model also explores how root depth, transpiration rate, antecedent soil moisture, and ponding event connectivity (time between ponding events) modify the required ponding duration for a given soil texture and vegetation type.

HYDRUS-1D modeling indicates that clay content is the dominant soil-based control on recharge feasibility. Soil textures with high proportions of sand or silt loam showed the most significant recharge potential. The presence of vegetation also significantly increases the required ponding duration for effective recharge, with modeling results showing a 27-fold increase in the median ponding duration requirement from bare soil to pasture grass, and additional increases in duration for the deeper-rooted plant types, such as deciduous trees. In management terms, basin designs that extend ponding duration, incorporate low-clay soils, and minimize evapotranspiration by plants are likely to be most effective for enhancing recharge. However, it is feasible to incorporate habitat objectives into the design of recharge facilities so long as the ET-related implications are acknowledged (see Guiding Principles for Enhancing Recharge and Habitat).

To improve the computational efficiency of this framework, a surrogate model was developed to approximate HYDRUS-1D simulation outputs across various soil, vegetation, hydrologic conditions. The surrogate model, based on a deep neural network, learns the nonlinear relationship between input parameters (e.g., soil texture, root depth, transpiration rate, ponding duration, and antecedent moisture) and recharge outcomes. To further enhance model accuracy near critical decision boundaries, an adaptive sampling strategy was implemented to iteratively select new simulation points in regions of high uncertainty or near the effective recharge threshold. This approach enabled fast prediction of recharge feasibility across the full parameter space while significantly reducing the time cost from traditional HYDRUS-1D simulations. This work emphasizes the importance of understanding subsurface behavior of infiltrated water as well as the need for more observational data to confirm the findings.

Forested Landscapes

The ATUR study is primarily focused on strategies to capture water that would be lost to the atmosphere, particularly via ET, as it represents the largest outgoing water flux in the natural hydrologic cycle. The state of Arizona includes large ponderosa pine forests, primarily along the Mogollon Rim/Transition Zone as well as other mountainous regions that feature multiple types of forests. Climate conditions in forested areas vary widely, but many are snow-dominated given high elevation settings. The potential for significant increases in capture and recharge in these areas is therefore a major theme in ATUR's research. A number of key messages have been developed that focus on how improved understanding of the hydrologic cycle along with changes in management of forested areas can increase recharge and/or subsurface water availability.

Key Message 3.2:
Forest thinning has been shown to reduce both ET and sublimation losses (direct loss of snow to evaporation). It can enhance water availability through increasing snow water equivalent (SWE), raising the liquid water input (LWI), and/or reducing sublimation. Some post-thinning forest patch size and geometry combinations enhance snow accumulation and persistence more than others. These benefits increase water availability, but the quantity of potential capture and recharge depends strongly on local climate and geology.

Evapotranspiration (ET) is the dominant outgoing water flux in arid and semi-arid regions, where it can account for over 100 percent of annual precipitation in some areas (see **KM** 2.2). Because ET strongly governs water availability, management actions that reduce atmospheric water loss, such as forest thinning, can produce substantial hydrologic benefits. Forest thinning for fire risk reduction can also help reduce erosion, stream downcutting, and loss of spring and base flows. By decreasing canopy surface area, leaf area index (leaf area per ground area), and interception, thinning overall reduces water stored in the canopy, stand-level transpiration demand, and total ET volumes compared to non-thinned forests (Simonin et al., 2007; Sankey et al., 2025). These reductions in canopy water use subsequently increase soil moisture and enhance water availability throughout the root zone, while also reducing competition among remaining trees (O'Donnell et al., 2021; Tatum et al., 2025). As a result, individual trees in thinned stands maintain higher canopy moisture, faster growth, and improved resistance to drought-induced water stress relative to those in non-thinned forests (Sankey and Tatum, 2022).

Ponderosa pine forests across much of Arizona largely consist of relatively young, dense stands of trees due to over a century of forest management practices including logging, grazing, and the suppression of natural wildfire (Covington and Moore, 1994). These dense, high-canopy cover forests are now experiencing more frequent and catastrophic wildfires, insect outbreaks, and increased vulnerability to heat and drought associated with climate change in recent decades (Breshears et al. 2013, Hammond et al. 2022). To reduce wildfire risks, Arizona is conducting the largest forest restoration effort in the US, known as Four Forest Restoration Initiative (4FRI). While the primary goal of 4FRI is to decrease wildfire risk and associated catastrophic flooding, the program's treatments produce other benefits (Sankey et al., 2021). Thinning reduces tree water stress and growth losses during drought, and there is clear evidence that the treatments also increase both canopy moisture in the remaining trees (Sankey et al., 2021) and soil moisture in the thinned forest (Belmonte et al., 2022; Sankey and Tatum, 2022; Tatum et al., 2025) as well as snow accumulation on the ground (Sankey et al. 2015; Belmonte et al., 2021; Donager et al., 2021; O'Donnell et al., 2021; Broxton et al., 2025).

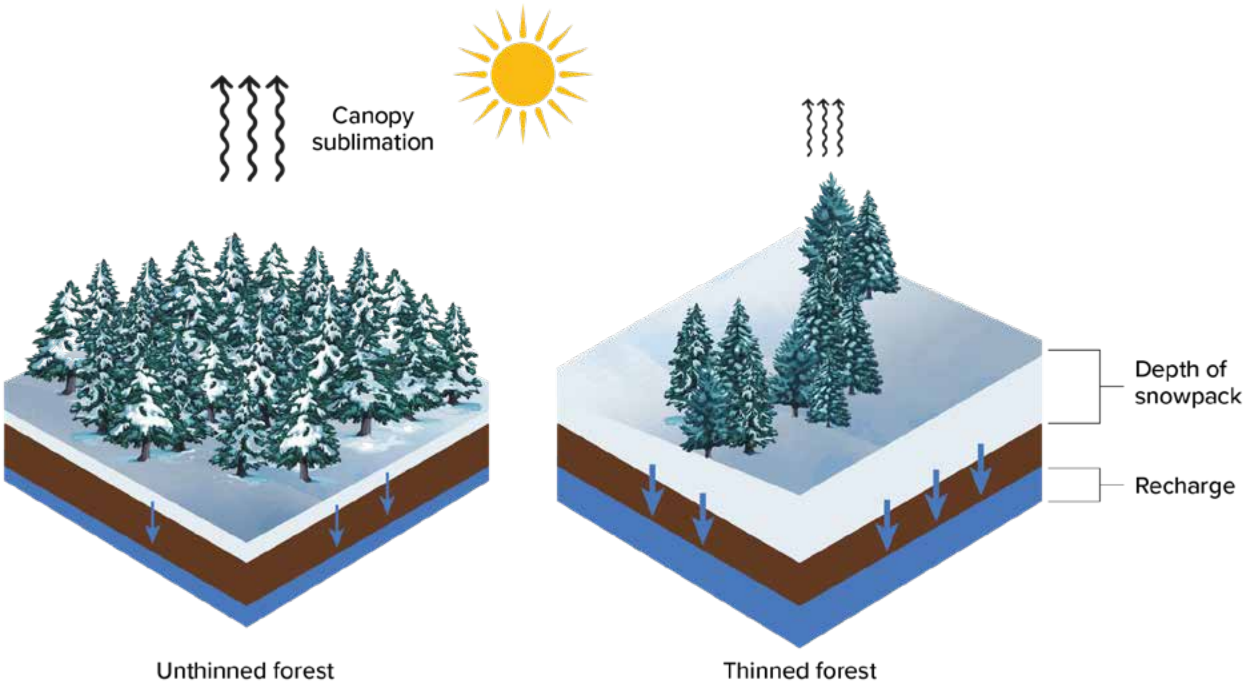


Figure 3.3. Sublimation involves snow directly becoming water vapor without melting. In unthinned forests (left side), more snow is caught in the canopy, leading to increased sun exposure and sublimation. These factors lead to reduced snowpack, thereby reducing water available for groundwater recharge. Thinned forests (right side) can reduce sublimation and increase depth and persistence of snowpack. Longer lasting snowpack leads to slower melting, which increases the likelihood of groundwater recharge. The geometry of the tree canopy matters; stands of trees that maximize northside shade have the most potential for persistent snowpack and recharge. (Source: Broxton et al., 2025; Figure Credit: Howe)

Using in-situ evapotranspiration measurements and ECOSTRESS satellite images, we documented that thinned ponderosa pine forests transpire significantly less water compared to adjacent non-thinned forests (Sankey et al., 2025). In-situ measurements collected 5 years post-thinning treatment in northern Arizona indicate that ET is reduced by 24% via thinning, whereas ECOSTRESS satellite data indicate up to 58% reduction in ET (noting that ECOSTRESS satellite estimates have been documented to overestimate ET in Arizona's arid and semi-arid environments). Using these estimates as a potential range of ET reductions, we estimate that ET reductions of this range across 10% of Arizona's ponderosa pine forests, which were identified as highly suitable areas for thinning, could result in up to ~1600 ac-ft/day in water savings. In-situ measurements document significant reductions in ET from thinning due to reduced tree density and total canopy area.

Beyond stand-scale ecological responses, thinning produces measurable basin-scale hydrologic changes. Modeling studies in central Arizona's highlands demonstrate that reducing ET through thinning increases both seasonal and annual streamflow, particularly during winter when lower canopy interception and reduced transpiration allow more precipitation to reach the soil and contribute to runoff (Baker, 1986; Moreno et al., 2016). Overall, thinning lowers atmospheric water losses and increases the proportion of precipitation that remains available for soil storage, vegetation use, and streamflow generation.

A high-resolution snow model (SnowPALM, Broxton et al., 2015) was used alongside in-situ measurements to study how forest thinning affects snowpack under warmer/drier and colder/wetter climate conditions and to offer insights for managing forests to increase snow pack duration and liquid water input (LWI; remaining water after interception and sublimation losses), which are both important factors for enhancing forest health, streamflow contributions, and potential groundwater recharge (Broxton et al., 2025). Increasing LWI increases soil moisture and can enhance plant water use, streamflow, and deep percolation (and thus recharge potential). Increasing snow cover duration can reduce stress on vegetation by providing available water during the pre-monsoon drought period.

Broxton et al. (2025) showed that overall, a reduction in canopy cover generally led to a reduction of interception losses and thus, greater LWI regardless of climate. Additionally, forest thinning tended to decrease snow cover duration under cooler and wetter climates found at high elevations (such as the White Mountains of eastern Arizona). However, for warmer and drier climates (such as those found along much of the Mogollon Rim), forest thinning generally had a smaller effect on snow cover duration.

We also found that the responses of the snowpack depend on the forest patch geometry as described by the sizes of canopy gaps and the aspect (compass direction) of canopy edges. Forests with larger gaps are best for enhancing snow accumulation and LWI, while shaded gaps (e.g. on the north sides of canopy stands) are best for minimizing snow ablation and enhancing snow cover duration. As such, there are trade-offs between enhancing LWI (by reducing canopy cover and increasing gap size) and preserving or enhancing snow cover duration (by reducing exposed south-facing canopy edges through smaller/narrower east-west oriented gaps).

Overall, significant opportunities for enhancing water supply and recharge can be achieved by forest managers if they take tree density, slope, aspect and the forest patch geometry/shading into account as they design their forest thinning strategies.

In contrast to findings related to forest thinning, prior work in riparian areas has not documented significant long-term water supply advantages associated with removal of invasive riparian vegetation, such as salt cedar or Russian olive. This is primarily because native vegetation tends to rebound quickly and offset the water savings (Annotated Bibliography: Riparian Management).

Key Message 3.3:
Ecological disturbances driven by increasingly hot and arid conditions, such as landscape-wide tree mortality and wildfires, are already affecting quantities and locations of capturable water in Arizona's forests. Pre-fire watershed management and flood control efforts can potentially facilitate water harvesting and limit storm damage from post-fire runoff events and associated large-scale erosion.

Disturbances that significantly alter vegetation structure, such as severe wildfires or drought-induced forest die-off, have the potential to affect the hydrology of that ecosystem. When ecosystems are severely disturbed, the vegetation that grows back may differ from what was there before. Depending on the specific details of pre-existing vs. resultant vegetation, there can be notable changes to interception of rain and snow, runoff, evapotranspiration (ET), and thus, water available for capture and recharge.

Not all disturbances or locations will yield the same responses to rapid vegetation change, including those induced by fires. Drier forests tend to be more hydrologically sensitive than those that receive greater mean annual precipitation, with hydrologic changes occurring on a shorter timescale (Li et al., 2017). Changes to forest cover in drier regions result in a larger percent change in streamflow or recharge compared to wetter regions. Loss of tree cover has the potential to reduce interception, leading to increased runoff during rain events. Drastic reductions in canopy cover can lower snowpack retention due to reduced shading and increased sublimation (Jones et al. 2020, also see section above). The high variability of annual precipitation, the magnitude of potential water losses to ET vs. precipitation, and the range of forest and vegetation types in Arizona imply a wide range of responses to future climate across the state (see **KM** 2.9).

High severity burns can create hydrophobic soil layers, significantly reducing infiltration rates, which is more pronounced in arid environments with already limited water retention capacity (Beatty et al, 2013; Chen et al, 2020; Van der Sant et al, 2018). Reductions in infiltration capacity can lead to dramatic increases in runoff and erosion, causing mass wasting in steep environments. Simultaneously, wildfires can reduce transpiration by eliminating vegetation, which directly lowers water use and increases supplies available for streamflow or groundwater recharge (Poon and Kinoshita, 2018; Collar et al, 2022). Impacts to post-fire ET are not permanent, and ET rates can recover quickly depending on vegetation regeneration (Poon and Kinoshita, 2018; Poulos et al, 2021). While reductions in ET can enhance streamflow generation by increasing available water, the extent of this effect depends on the proximity of streams to burn scars, as unburned vegetation between burned areas and streams may reabsorb the additional moisture and limit the amount of available water for enhanced streamflow or recharge (Hallema et al 2017; Collar et al, 2022). Although the hydrophobic soils generally hinder groundwater recharge within burn scars, wildfire induced flooding can temporarily increase recharge downstream or adjacent to burn scars. In the Western US, streamflow has often been shown to increase across all seasons and for several years post-wildfire (Williams et al. 2022). With the amount of land area burned increasing, there are growing opportunities for pre-fire watershed protection and flood control efforts that facilitate water harvesting and limit potential storm damage from post-fire runoff events.

Severe post-fire disturbance management options include erosion control/runoff and sediment capture and careful revegetation planning to maintain desired forest structure and patch geometry (as discussed in Broxton et al., 2025). In-stream flood control structures are increasingly used to mitigate elevated runoff and sediment transport in post-fire landscapes. While these interventions are primarily designed to attenuate peak flows and trap sediment, they may also provide ancillary hydrologic benefits by enhancing infiltration and groundwater recharge. Small rock dams installed within channels retain surface water and generate localized ponding, thereby increasing water residence time and promoting infiltration into underlying soils. This process can augment infiltration in the stream channel and contribute to small-scale recharge. Depending on underlying geology, detention basins constructed at watershed outlets may similarly facilitate recharge. Consequently, post-fire flood mitigation infrastructure designed for flow and sediment control may also yield measurable recharge benefits.

Growing wildfire activity in Arizona means these interventions should no longer be viewed as emergency responses after the fact, but rather part of a broader strategy for protecting capturable water under hotter, drier conditions. Because post-fire runoff and sediment pulses can rapidly degrade downstream infrastructure, reservoirs, and recharge opportunities, managers should consider placing flood-control and erosion-control treatments where they will intercept damaging flow while also maximizing the chances that detained water becomes stored locally. This motivates a spatial screening approach that uses readily available geospatial datasets to identify stream reaches where in-stream structures can simultaneously reduce post-fire flood impacts and enhance water harvesting potential.

Suitable locations for in-stream structures can be identified using GIS-based screening that links post-fire hydrologic risks (runoff and sediment) with the places where added water residence time is most likely to translate into infiltration and localized recharge.

A preliminary suitability analysis was conducted for northern Arizona near Flagstaff (Fig. 3.4), a geomorphically diverse, tectonically stable landscape of steep volcanic uplands and narrow alluvial valleys where ephemeral channels are highly responsive to disturbance and restoration. To identify candidate reaches, multiple geospatial layers were compiled—including digital elevation models (to derive slope and flow accumulation), surficial geology, soils (e.g., porosity or infiltration-related properties), and land cover—and then filtered to highlight favorable conditions such as relatively gentle channel gradients, convergent flow paths, and permeable alluvial settings. These layers were overlaid to map reaches that met criteria across datasets, yielding at least 86 ephemeral stream segments suitable for in-stream structures across the study area. By prioritizing reaches with both high runoff concentration potential and high infiltration capacity, this approach helps target projects where structures designed for flood attenuation and sediment capture may also produce ancillary benefits by increasing water residence time, enhancing transmission losses, and supporting small-scale recharge—outcomes that are especially valuable as burned area and post-fire runoff hazards increase. Although the conditions used to create this map are specific to northern Arizona, land managers can utilize a similar approach to identify suitable streams in their location.

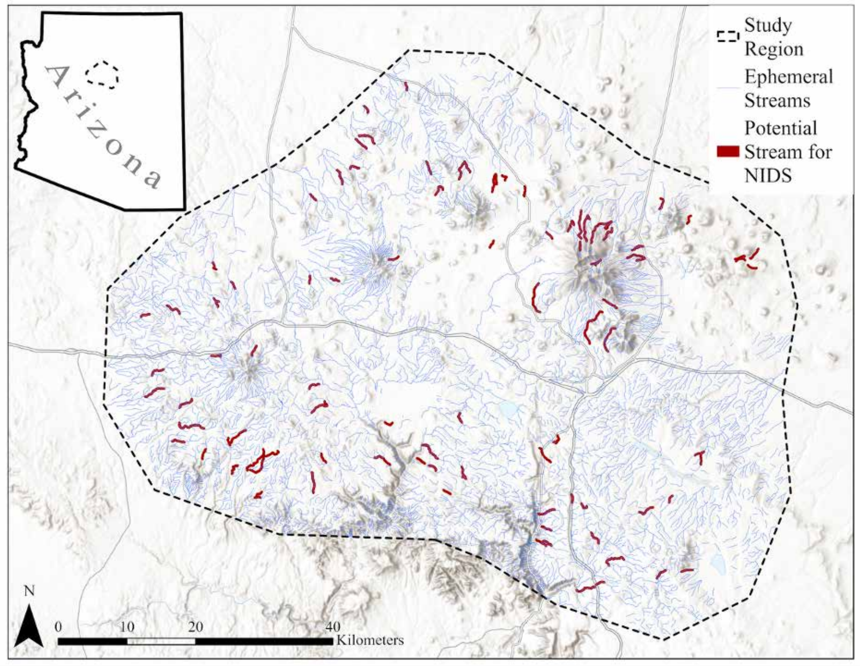


Figure 3.4. Ephemeral streams surrounding the San Francisco Volcanic Field that could potentially benefit from natural infrastructure in dryland streams (NIDS) based on GIS suitability analysis (Source: Lewis).

Riparian Areas and Grassland Landscapes

Groundwater-dependent ecosystems, including riparian areas, springs, and wetlands exist throughout Arizona. With declining groundwater and base flow (streamflow supported by groundwater), these ecosystems are under significant stress because they require shallow water tables and have little tolerance for drying (Stromberg et al. 1996; Bromley et al. 2026). Thoughtful design and location of recharge enhancement efforts can support ecosystem functions, services (including protection of culturally important species), and habitats, while also enhancing water supplies. Protection of landscapes and features with high recharge potential, such as floodplains and ephemeral channels, can help maintain natural recharge fluxes. Stormwater from nearby urbanizing areas has the potential to enhance habitat restoration and groundwater storage through infiltration and recharge in these natural areas (see Groundwater Recharge and Environmental Enhancement Opportunities in Grasslands in Arizona).

Removal of non-native (invasive) plants along stream channels has not been shown to reduce evapotranspiration in arid regions but can support re-establishment of native riparian vegetation (Annotated Bibliography: Riparian Management). Land managers in the Southwest have long viewed removal of invasive riparian vegetation, which has high rates of water use, as a potential strategy for increasing water yields. After several decades, there is still inconclusive evidence on the potential for these efforts to enhance streamflow or groundwater recharge. Integrated hydrologic monitoring (i.e. of multiple fluxes) to characterize the entire water balance of an area treated for riparian invasives could provide invaluable decision support for future projects.

Stormwater Recharge Efforts in the San Pedro Watershed

There are few examples of stormwater recharge efforts across the state, though multiple strategies are being piloted within the San Pedro Watershed. The Coyote Wash Stormwater Management Project, managed by the Cochise County Flood Control District, (downstream) of urban Sierra Vista, is currently under construction as a pilot UER project. An 1800-acre proposed subdivision between the City and the San Pedro Riparian National Conservation Area (SPRNCA) was purchased and permanently protected with a conservation easement, to both preclude future pumping and allow for construction of the recharge project in this key location. Use of a MODFLOW groundwater model highlighted the benefits to the river of this recharge project, at this location, to sustain favorable groundwater conditions for SPRNCA's riparian vegetation. An abandoned gravel pit is being renovated to receive and detain UER floodwater after it is diverted from Coyote Wash. The flows will be slowly released back to the channel. The basin was sized and designed to essentially restore the predevelopment flood flows for the SPRNCA, downstream.

Urban Landscapes

Multiple strategies to maximize use of alternative water supplies are gaining interest in urban areas across Arizona, in part due to reductions in current and anticipated Colorado River deliveries through the Central Arizona Project (CAP) and increasing uncertainty about long-term water availability. Stormwater generated as a result of urbanization (i.e. "urban enhanced runoff" or UER) has been recognized as a potential water supply for decades, but as Arizona's water management challenges intensify, UER is receiving increasing attention as a source for recharge efforts, especially within highly urbanized watersheds where increase in impervious surfaces has dramatically altered hydrologic responses. Unmanaged UER leads to localized nuisance flooding that could be redirected toward more beneficial uses.

Key complexities of stormwater recharge efforts include the episodic nature of runoff, limited knowledge of subsurface hydrogeology, and limited land availability for recharge within developed urban regions. Limiting risk to lives and property is a flood manager's top priority, complicating efforts to reliably capture and recharge excess stormwater. Also, quantifying the amount of non-appropriated/appropriable (under surface water laws) "enhanced" runoff may require demonstrations of pre-development conditions. However, there is increasing evidence that extreme rainfall events as well as longer periods of drought will occur in the context of climate change (Fifth US National Climate Assessment, 2024). Given the need to manage increasing flood risks, the opportunities to integrate flood control more effectively into urban planning and recharge efforts needs further consideration (see Stormwater Recharge Efforts in the San Pedro Watershed box).

Following implementation of stormwater recharge features, monitoring and maintenance efforts are critical to assessing their performance and optimizing designs for the future. Monitoring of surface flows in the upstream and downstream watersheds prior to and post development of recharge features also allows for the development of stormwater capture estimates that can be used to verify model projections, identify limitations, and optimize system designs. Despite the importance of such data, relatively few stormwater recharge features in Arizona are actively monitored. Expanding monitoring efforts is essential to improving confidence in stormwater recharge estimates, understanding the impact on groundwater budget, and advancing the use of UER as a managed water supply.

Key Message 3.4:
Land use changes in watersheds adjacent to and within large cities are projected to result in increased impervious surface due to urbanization through 2100 in the Phoenix, Pinal and Tucson AMAs, with potential to generate greater quantities of urban enhanced runoff (UER), particularly during winter. This increase in UER presents opportunities for capture and recharge because this water is not yet appropriated and the majority of it would otherwise have evaporated.

The ATUR team used the Integrated Climate and Land Use Scenarios (ICLUS) dataset developed by the U.S. Environmental Protection Agency (EPA; Bierwagen et al., 2010; U.S. EPA, 2016) to project land use changes due to urbanization between 2030 and 2100, at the HUC-12 watershed scale (818 total watersheds), in the central/southern Active Management Areas (AMAs) within Arizona (Phoenix, Pinal, Tucson, Santa Cruz, Douglas and Willcox). Projections were based on the ICLUS model under Shared Socioeconomic Pathway SSP2 (hereafter referred to as the low emissions scenario) and SSP5 (hereafter referred to as the high emissions scenario) to represent a range of urbanization increases. The low emissions scenario estimates that US population will reach 455 million by 2100, whereas the high emissions scenario estimates the population to grow to 730 million by 2100. Across the 70-year projection period, watersheds surrounding existing urban centers show a larger percent change in urban areas under both low and high scenarios. (Figure 3.5).

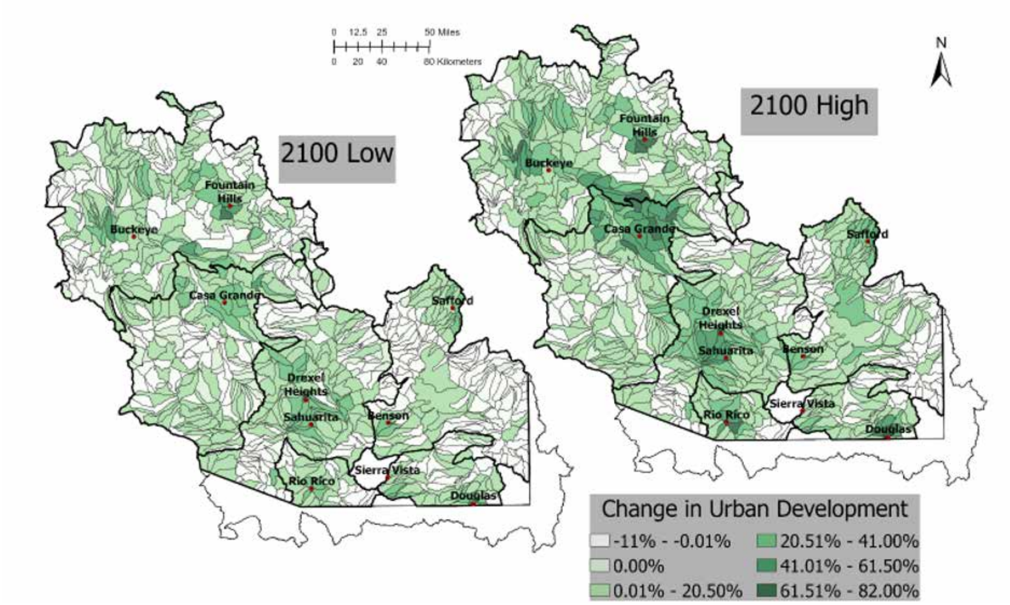


Figure 3.5. Percent change in urban areas across the 70-year projected period from 2021 to 2100. (Source: Ferrell, 2025)

Urbanization is projected to lead to a steady increase in runoff from 2021 through 2100 in the Phoenix, Pinal and Tucson AMAs under both scenarios. This increase in direct runoff volumes was estimated under multiple design storm durations (1-hour duration representing summer monsoons and 12-hour duration representing winter rainfall) and return intervals as per NRCS standardized methods.

Figure 3.6 summarizes mean runoff volumes across all HUC-12 watersheds in all southern AMAs for 1-hour and 12-hour design storms under baseline (current, 2021) and projected (2060 and 2100) low and high population growth scenarios. Across all storm durations and return periods, runoff volumes increase over the years, indicating a consistent upward shift in runoff generation as impervious cover expands. Differences between low and high population growth scenarios become more pronounced over time, highlighting the cumulative effect of urban development on runoff magnitude.

This study helped identify HUC-12 watersheds with highest projected urbanization across the southern AMAs in Arizona between 2021 and 2100. These watersheds have the highest potential for generating urban enhanced runoff that may be available for recharge.

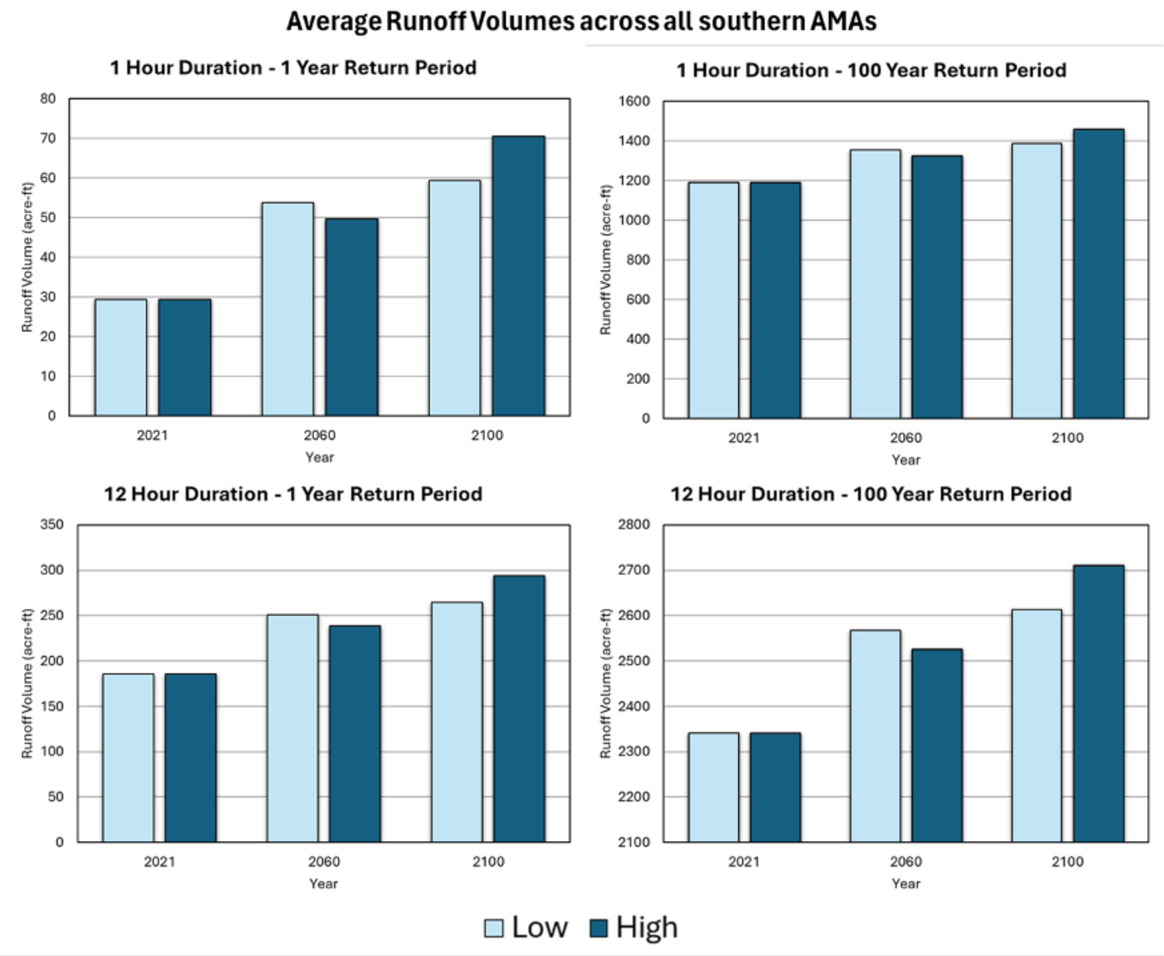


Figure 3.6. Summary of mean runoff volumes across all HUC-12 watersheds in the southern AMAs for 1-hour and 12-hour design storms under baseline (current, 2021) and projected (2060 and 2100) low and high population growth scenarios. The difference between projected and baseline runoff volumes is an indicator of urban enhanced runoff that presents opportunities for capture and recharge. (Source: Ferrell, 2025)

Key Message 3.5:
Working with flood managers and exercising the existing authorities of Arizona's Flood Control Districts may allow for increased integration of recharge opportunities into floodwater management practices and provide both community and ecosystem benefits.

While drought conditions exacerbated by climate change threaten water availability in Arizona, more intense precipitation events are expected to contribute to increased flooding across the state. These climatic phenomena combined with anticipated increases in UER present an opportunity for researchers and practitioners to simultaneously manage flood risks and enhance water supplies through the capture and recharge of floodwaters. Members of the ATUR research team met virtually with practitioners from Flood Control Districts (FCD) across the state in March 2024 to discuss challenges and opportunities at the intersection of flood control and groundwater recharge. Opportunities included taking better advantage of existing FCD authorities, collaboration with multi-stakeholder coalitions, more effectively articulating community and ecosystem benefits to integrating flood control with other co-benefits, and identifying areas for future research such as improved monitoring, water balance modeling and mapping within specific watersheds. The findings from this workshop are documented in the white paper titled Intersecting Flood Control and Recharge.

The Arizona Revised Statutes (ARS) provide FCDs with the authority to "construct, operate, and maintain artificial groundwater recharge facilities" and collaborate with other stakeholders engaged in recharge activities if the facilities "have flood control benefits" (Ariz. Rev. Stat. § 48-3603, 2025). Although the authority to combine recharge objectives with flood control exists, current flood control policies often prioritize threat mitigation rather than recharge potential. There is a general lack of funding available for integrating recharge projects into flood control efforts, and in many cases, insufficient data and staff to carry out these projects. Land access issues, including easements and right-of-way restrictions, pose challenges to recharge efforts. Water quality issues associated with urban runoff can also be problematic.

Despite these issues, FCD participants from across the state expressed enthusiasm about integrating recharge objectives with flood control efforts. Combining recharge and flood control efforts may increase funding options (because of funding available from other entities to support co-benefits), reduce peak flows and flooding hazards, increase potential for community engagement, and improve ecosystem health. Exploring innovative interagency partnerships with Tribes, Arizona Department of Transportation (ADOT), water/wastewater utilities, ADWR, and others may enhance funding opportunities to embed recharge objectives into flood control projects.

ATUR products, including estimates of urban runoff generated as a result of development, projections of changes to the hydrologic cycle as a result of climate change, and mapping of infiltration potential across the state, may help fill in knowledge gaps required to plan future recharge and flood control projects. Prioritizing recharge outcomes in the context of flood control has the potential to support new, unconventional partnerships, improve both habitat and community health, and transform flood waters from a liability into an asset.

Key Message 3.6:
Drywells and retention/detention basins are strategies to manage and capture stormwater for recharge in urban regions. In the Phoenix Active Management Area, the ATUR team estimates that over 94,000 acre-ft per year (over 35% of the total runoff generated) on average was captured and infiltrated annually from drywells and retention basins from 2010–2020.

Estimates indicate that drywells and retention/detention basins in the Phoenix AMA currently capture approximately 94,300 acre-ft of stormwater annually, a volume that could rise to 165,000 acre-feet by 2058 under projected urbanization and climate scenarios. These capture volumes indicate that changes in the management of stormwater could be a critical strategy for enhancing water supply reliability.

These figures were derived using a novel, spatially distributed modeling framework designed by ATUR researchers to quantify stormwater capture in regions lacking detailed infrastructure maps. The assessment integrated open public records (such as state drywell databases) with high-resolution LiDAR topography data to map and characterize the storage capacity of drywells and retention/detention ponds across the Phoenix AMA, overcoming significant gaps in historical data. By coupling these infrastructure layers with curve number-based runoff estimates, captured runoff volumes were calculated under historical conditions (2010-2020) and projected future scenarios (through 2058) that account for both climate change and urbanization.

While the estimated captured volume may appear high to some observers, this analysis is based on conservative assumptions. As new developments create impervious surfaces (generating more runoff), they are mandated by Maricopa County to install stormwater management practices (SMPs) (e.g., City of Phoenix Stormwater Policies and Standards manual, §3.8; Maricopa County Flood Control District Drainage Policies and Standards, §6.3). For example, in the City of Chandler, stormwater infrastructure is designed to retain 100% of runoff. In newly developed areas along the metropolitan outskirts where Stormwater Management Practices (SMPs) are mandated but high-resolution LiDAR data was unavailable, the analysis applied a relatively low value for retention basin coverage (Su et al., 2025).

However, a critical distinction must be made between surface capture and aquifer recharge. While the infrastructure successfully intercepts these substantial volumes of water, site-specific conditions, such as soil texture or uptake by vegetation, can limit deep percolation and recharge. ATUR researchers are now working to convert these “potential” estimates into “realized recharge” rates by deploying physically-based vadose zone modeling and AI-driven surrogates which have lower computational demands and are trained on outputs of physically-based simulations. Future efforts could combine the AI-driven surrogate models with in-situ monitoring of soil moisture dynamics and deep percolation rates to precisely estimate realized recharge, eventually enabling water managers to move beyond treating stormwater as a nuisance and liability, transforming it instead into a measurable asset for aquifer sustainability.

Key Message 3.7:
Research linking green stormwater infrastructure (GSI) to groundwater recharge is limited. However, models and studies show that GSI practices such as roof runoff harvesting, rock detention structures, and retention basins in semi-arid and arid regions can reduce peak floodflows while increasing infiltration and/or providing water for landscape irrigation demands.

The green stormwater infrastructure (GSI) literature in arid and semi-arid regions is concentrated around a small number of practices, outcome metrics, geographic regions, and modeling approaches. Across studies reviewed by the ATUR team, the most frequently examined GSI practices are retention basins and rainwater harvesting systems, followed by permeable pavement and green roofs, with retention-based systems appearing in the majority of research papers either alone or in combination with other practices. In our literature review, the term retention basin is used broadly to describe systems designed to temporarily store and infiltrate stormwater, encompassing a range of basin-scale retention or detention configurations.

A consistent finding in the literature is that GSI practices are effective at reducing runoff volumes and attenuating peak flows by increasing in-situ storage under a range of storm conditions. Studies evaluating retention basins, rainwater harvesting systems, permeable pavement, and green roofs repeatedly demonstrate reductions in total surface runoff relative to conventional urban drainage configurations, particularly for smaller to moderate storm events. In addition to reducing runoff volumes, GSI practices are shown to delay and lower peak discharge, flattening hydrographs and reducing downstream flood risk.

Existing studies generally evaluate the efficacy of GSIs by measuring surface impacts, such as captured runoff volume, storage capacity, and reduction in peak flow. In contrast, subsurface processes like infiltration volume are evaluated less frequently, and water quality outcomes are included in an even smaller subset of studies. While it is well-established that GSIs provide valuable flood control and habitat benefits, their actual capacity to make meaningful contributions to groundwater recharge remains unclear without more dedicated monitoring.

Guiding Principles for Enhancing Recharge and Habitat

The following suggestions are derived from a synthesis of work across the ATUR team:

Maintain and enhance natural hydrologic system functions

- Avoid constricting floodplains and natural channels to permit natural flood attenuation and support healthy ecosystems
- Prevent erosion to retain soil moisture and shallow groundwater that contributes to baseflow and habitat (i.e., avoid actions that lead to dewatering of soils)
- When restoring land after disturbance, reseed/replant with native and deep-rooted grasses/plants to enhance infiltration and support well-adapted habitat types

Support healthy forests and limit high-intensity wildfires

- Limit catastrophic wildfires that lead to high levels of erosion, through reductions in fuels and forest thinning
- Protect/enhance ground cover to slow runoff, improve water quality, and reduce erosion
- Manage forest thinning to enhance shading of snowpack to limit sublimation and promote recharge
- During post-fire restoration, incorporate recharge objectives and growth of species that can withstand increasing temperatures and drought

Encourage recharge in naturally suitable areas

- Enhance delivery of surface runoff to ephemeral streams in alluvial basins (to limit water losses due to evaporation)
- Enhance delivery of surface runoff to fractured bedrock and karst areas (while ensuring water quality issues are addressed)
- Integrate recharge objectives into land use, flood-control and drainage infrastructure designs
- Avoid development that increases impermeable areas in locations that have high recharge potential
- Detain water in areas of high soil permeability near runoff source
- Design flood-control structures to promote recharge in floodplains or other highly permeable areas
- Encourage urban stormwater capture near impervious source areas to minimize erosion and ET and protect water quality; facilitate delivery to recharge zones
- Maximize ponding time in recharge zones (while incorporating pest control measures

Acknowledge and account for water and maintenance requirements of enhancing environmental/habitat quality

- Plan for water supply tradeoffs of promoting enhanced habitat through ponding and increased soil moisture.
- Ensure appropriate maintenance of coordinated flood control/recharge facilities (e.g. check dams, detention basins, roadside features) to maintain functionality over time (e.g. due to sedimentation issues).
- Improve water quality with soil-aquifer treatment if possible; manage possible increased risks to groundwater from urban runoff (e.g., through dry well construction standards).

Statewide Suitability Analyses of Select Capture and Recharge Strategies

ATUR researchers have compiled and analyzed data across the state to evaluate regions of suitability for multiple capture and recharge strategies. These datasets have been integrated into publicly available tools to assist natural resource managers in analyzing recharge suitability and prioritizing areas and strategies for enhanced capture and recharge. These analyses use publicly available datasets, including The University of Arizona SWE dataset (Broxton et al, 2019), National Land Cover Database (NLCD), National Soil Geographic Database from USDA-NRCS, and USGS mapping of lineaments and karst (limestone) topography, among others. One such analysis maps suitability for thinning in Arizona's ponderosa pine forests to reduce evapotranspiration and enhance groundwater recharge. The Multi-Criteria Decision Analysis (MCDA) process is a decision-support approach that synthesizes multiple spatial criteria using expert defined weights to systematically evaluate landscape suitability for a given objective (Malczewski and Rinner 2015). GIS-MCDA has been used widely to map groundwater recharge suitability across other regions and strategies (Fathi et al., 2021; Rahman et al., 2012; Raja Shekar and Mathew, 2023; Shaban et al., 2006). Integrating GIS layers such as vegetation density, soil properties, topography, and other factors in different weighted combinations using MCDA generates a powerful strategy for determining recharge suitability.

As part of developing suitability analyses for evaluating and mapping regions for enhancing groundwater recharge across Arizona, ATUR researchers have developed an Analytical Hierarchy Process (AHP) tool for MCDA. The AHP tool allows the user to input the variables that influence the suitability (e.g. karst topography, lineament density, permeability, and porosity) and conduct a pairwise comparison of each variable to determine the overall relative weights (i.e., their relative importance to total suitability) to be used in the analysis. This weighted combination of relevant parameters based on the literature can be used to support decision-making for where to site potential recharge enhancement projects. An example weighting structure (Lima et al., in review) is illustrated in Figure 3.7.

ATUR researchers also developed a Subsurface Infiltration Index (SbII) using the aforementioned MCDA process to estimate the infiltration potential of water into the subsurface across Arizona. This index considers permeability, porosity, lineament density, and the presence of karst topography to provide a relative measure of infiltration capacity on a scale of 1–10, where a higher SbII indicates higher suitability for infiltration. The Soil Moisture Infiltration Index (SMII) is another index (scaled 1-10) created to determine where on the landscape water is likely to accumulate and infiltrate into the soil, considering soil hydraulic conductivity and surface properties such as aspect, slope, relative elevation, and landscape convexity or concavity. These surface properties have been combined into their own index, the Topographic Relative Moisture Index (TRMI, also scaled 1-10). Maps showing values of SbII, SMII, and TRMI statewide are linked here for use.

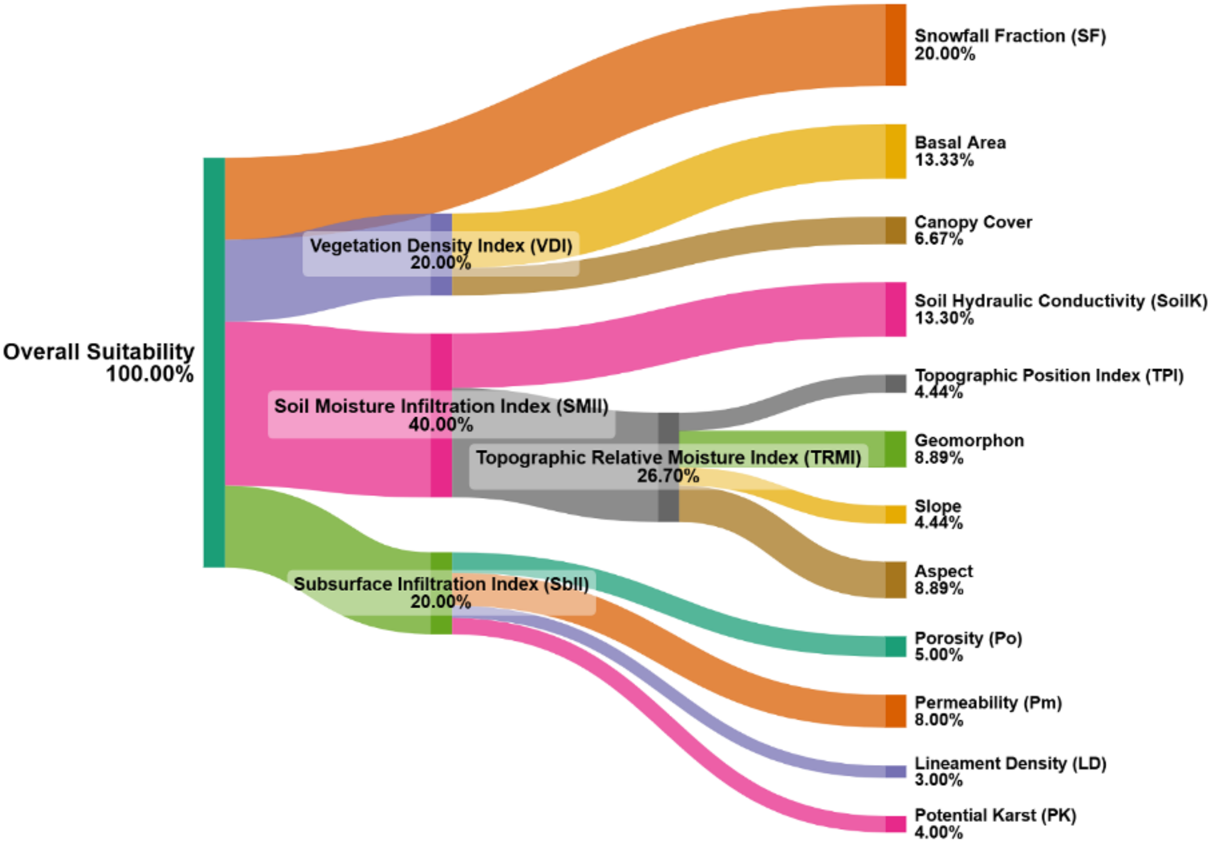


Figure 3.7. Sankey diagram showing the results of the MCDA process for evaluating the overall suitability for ponderosa pine thinning to enhance recharge in Arizona. Variables that influence suitability (Basal Area, Canopy Cover, Soil Hydraulic Conductivity, Topographic Position Index, etc.) are combined based on their relative weights into indices (Vegetation Density Index, Soil Moisture Infiltration Index, Topographic Relative Moisture Index, & Subsurface Infiltration Index). These indices are then combined to evaluate overall suitability. (Source: Lima et al., in review)

Suitability Analysis 1: Forest Thinning

Key Message 3.8:
Statewide mapping shows that forest thinning in Arizona's ponderosa pine forests can enhance recharge and provide a water-capture co-benefit. Of the 1.4 million hectares of ponderosa pines statewide, about 46% (588,992 ha, 1.45 million acres) is highly suitable and 2.4% (30,920 ha, 76.5 million acres) is very highly suitable for thinning with recharge enhancement as co-benefit.

Areas suitable for thinning to reduce evapotranspiration and enhance groundwater recharge in Arizona's ponderosa pine forests were assessed using the aforementioned indices (SbII, SMII, and TRMI) along with snowfall fraction (UA SWE data), a Vegetation Density Index that considers basal area (tree trunk cross-sectional area per acre), and canopy cover (percentage of ground shaded by leaves). These layers were spatially analyzed to determine overall suitability for enhancing groundwater recharge through forest thinning on a scale of 1 to 10 (Lima et al., in review). Results of this analysis indicate that of the 1.4 million hectares of ponderosa pine forest in Arizona, approximately 46% (588,992 ha) is highly suitable (>7), while about 2.4% (30,920 ha) is considered very highly suitable (>8). This overall suitability has been mapped across the state to help forest managers consider recharge enhancement as a co-benefit while planning and prioritizing areas for thinning (Fig 3.8).

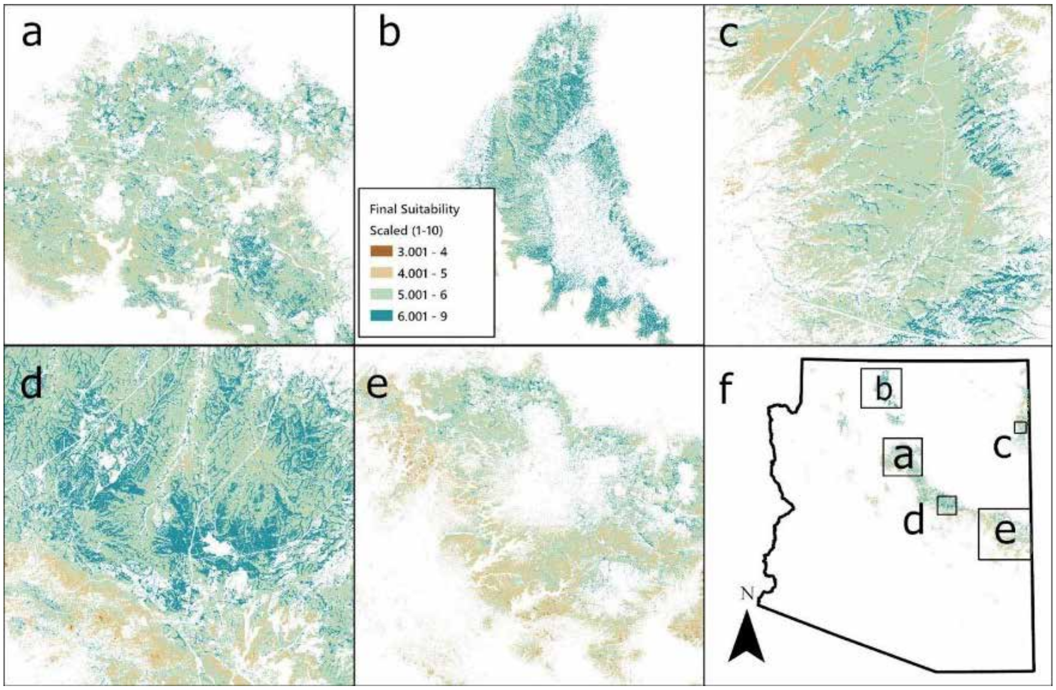


Figure 3.8. Final suitability ratings where thinning is most likely to enhance groundwater recharge in Ponderosa Pine (Pinus Ponderosa) forests. Cooler colors indicate higher suitability while warmer colors indicate lower suitability. Suitability is highest in the forested areas near the San Francisco Peaks (a), the Kaibab Plateau (b), the Defiance Plateau (c), the Mogollon Rim (d), and the White mountains (e), the highlighted areas are shown in panel f. Suitability values >= 6 are found primarily in areas with dense snow-dominated forests underlain by carbonate as evidenced by the large areas of high suitability along the Kaibab Plateau and Mogollon Rim (b and d). Less snow dominated and south facing sites, and sites underlain by volcanics or non-karst have lower suitability values particularly the southern edge of the Mogollon Rim (d) and southern flank of the White Mountains (e). (Source: Lima et al., in review).

We emphasize that there are consequences associated with changing components of the hydrologic cycle, and environmental assets should be inventoried and protected in the context of any proposed new capture and storage projects. The section called “Guiding Principles for Enhancing Recharge and Habitat” was created in part to address this issue.

Suitability Analysis 2: Flood-enhanced recharge potential

Key Message 3.9:
The statewide suitability tool for the use of floodwaters to enhance recharge allows identification of regions with high recharge potential. It can provide justification for more targeted local surveys to quantify actual recharge and inform local management practices.

A suitability analysis was developed and performed using a topographic flood model based on landscape geomorphic features and the subsurface infiltration index (SbII) with soil hydraulic conductivity to identify areas across the state where floodwater may be available for enhanced groundwater recharge. The analysis considers both the potential for localized flooding and the infiltration capacity of the soil and subsurface. Topographic variables such as topographic wetness index (TWI, a commonly used metric to quantify the impacts of topography on water accumulation; higher TWI indicates higher likelihood of inflows leading to saturation, and ponding), watershed elevation anomaly (the difference between the local elevation and the median elevation of the watershed), and geomorphon (flat, peak, ridge, shoulder, pit, valley, etc.) were used to identify areas of flood risk. While other flood risk models utilize precipitation and land use/land cover data, this model only considers stable topographic values, which helps avoid the issues of data gaps, particularly across Federally Recognized Tribal lands in Arizona, and makes this a simple analysis for areas with limited data availability or computational resources. For areas where the data were available, results of the flood risk mapping were validated with the US Federal Emergency Management Agency (FEMA) National Flood Hazard Layer (NFHL) mapping for Arizona, where 75% of the modeled pixels coincided with the NFHL high risk zones.

Flood risk and infiltration capacity (determined from SbII and soil hydraulic conductivity) were combined to determine the potential for flood enhanced recharge (FER) across the state. This suitability analysis can be used as a screening tool prior to applying additional layers (hydroclimatic, socioeconomic, etc.) for more specific analyses. The results show the greatest FER potential in the Basin and Range physiographic province, particularly in the Black Rock and Goodwin Washes (on the San Carlos Apache Reservation, northwest of Safford, AZ), near the San Pedro River, and areas in the southwest corner of the state. FER potential is limited in the Mogollon Rim region given its mountainous terrain; however, areas of the Salt River up and downstream of Theodore Roosevelt Lake show higher potential in the region. While the Colorado Plateau has relatively lower flooding potential, presence of karst and faults/fractures in this province yield areas of high FER suitability near White Mesa (east of highway 89), the Little Colorado River, and the region north and east of Hopi Bute (west of highway 191, near Greasewood on the Navajo Nation) (Figure 3.9).

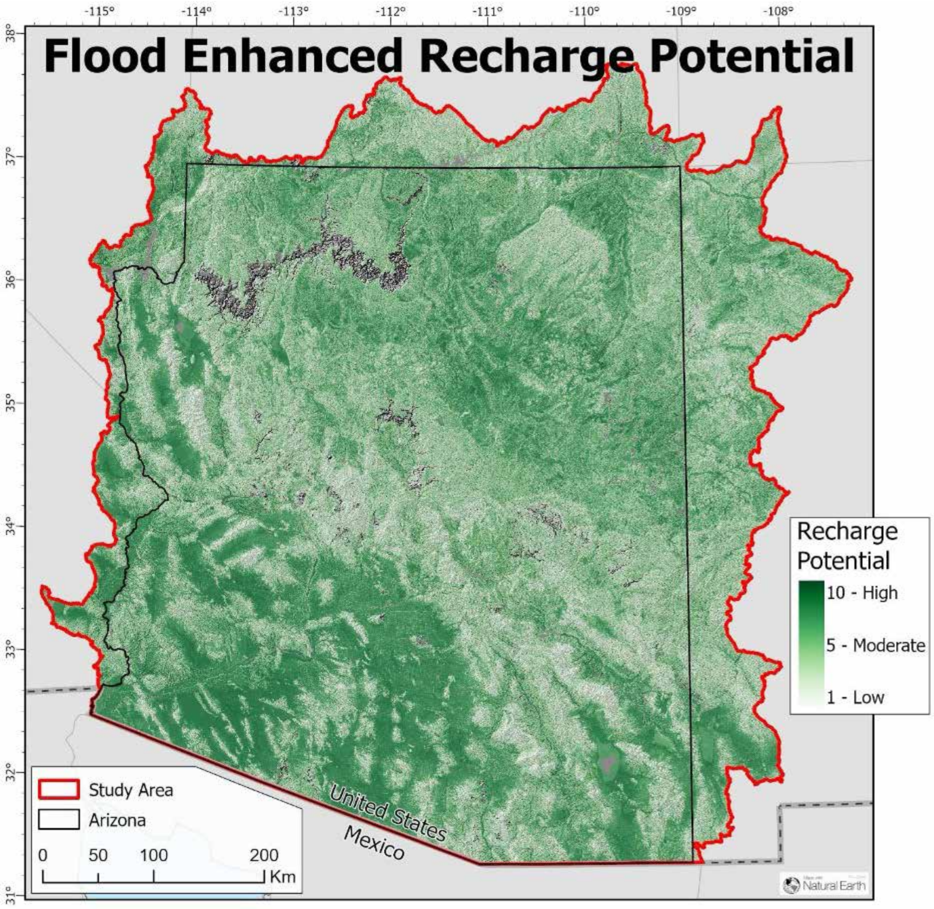


Figure 3.9. Floodwater enhanced recharge potential across the state of Arizona. Recharge potential is calculated as the weighted sum of flood potential (50% weight), soil saturated hydrologic conductivity (a.k.a. soil K; 20%), and subsurface infiltration index (30%). Special attention should be paid to retaining floodwaters in areas where recharge potential is high, and downstream recharge potential is reduced. Gray areas, with hillshade, indicating no data. (Source: Zalesky et al., in review).

Karst-related features

Key Message 3.10:
Karst aquifers (including limestone and related rock types) are critical to Arizona's water resources; they support municipal water supplies, sustain base flow in rivers and streams, and feed ecologically important springs. Karst landscapes–characterized by internal drainage, rapid infiltration, and direct connection between surface and groundwater–offer unique opportunities for recharge enhancement.

This study produced the first state-wide, spatially consistent map of lineaments (linear features generally indicative of subsurface geologic features with secondary porosity such as faults, joints, and fracture zones). Work is underway to improve on lowest resolution maps of potential sinkholes to create a more accurate and higher resolution map of sinkhole density across Arizona. Novel techniques were created and implemented to verify these features. Topographic analyses were conducted and data were published to help guide future studies of karst. Karst or karst-prone lithologies (rock types subject to dissolution and the formation of sinkholes, caves, and conduits), underlie a significant percentage of the state).

Karst aquifers can quickly and readily recharge water, even to depths of 1,000s of feet and make it readily available for recovery. However, the characteristics that make karst aquifers ideal for recharge also can, but not always, make them particularly vulnerable to contamination and make flow paths unpredictable. The high hydraulic conductivity of karst conduits allows constituents dissolved and suspended in water to move quickly with limited natural attenuation, creating elevated risks to drinking water and sensitive ecosystems. Enhancing recharge in karst areas and protecting water quality both require informed and deliberate land-use planning, thoughtful water source protection, coordinated research and targeted monitoring. Expanding research efforts and creating a comprehensive state-wide database of karst features–including sinkhole, sinking streams, springs, and subsurface connections–will provide the foundation for effective management, protection, and the sustainable use of water resources in Arizona's karst landscapes.

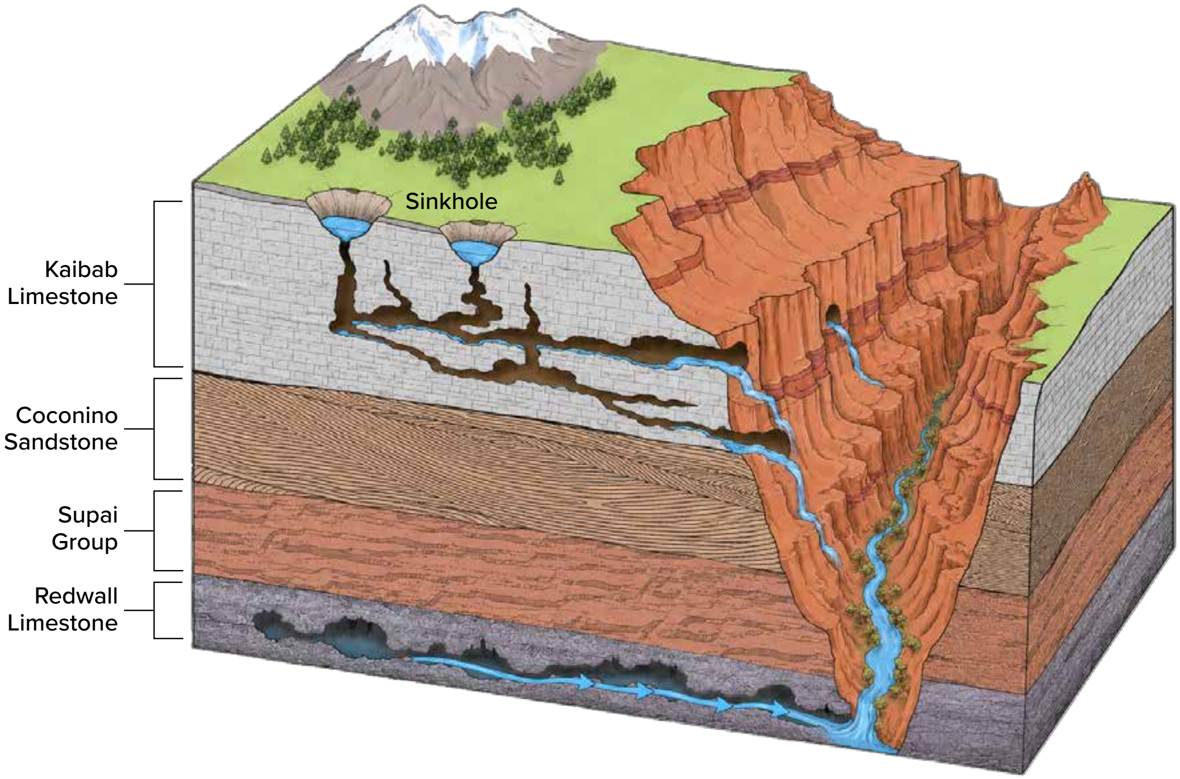


Figure 3.10. Karst aquifers are characterized by subsurface drainage networks and fracture-controlled infiltration pathways. These systems play a critical role in Arizona's water resources by connecting surface water to groundwater through rapid infiltration and structural conduits, making them important targets for managed aquifer recharge while also presenting vulnerabilities to contamination. (Source: C. Mroczek, 2025, Figure Credit: Mohsenzadeh Karimi; Mroczek)

Lineament Density

Key Message 3.11:
Lineament density (density of fault-related features) is a widely used indicator of enhanced infiltration potential and a common factor or thematic layer used in analyses for recharge suitability and in identifying potential recharge zones in bedrock environments.

Lineaments are linear or curvilinear features on Earth's surface which often correspond with underlying geologic structures such as faults, fractures, folds, joints, and shear zones. High lineament density has been shown to correspond to higher well yields and greater permeability and to greater recharge. A semi-automated method was used to extract lineaments statewide using a 10-m digital elevation model (Figure 3.11). This dataset is available on HydroShare and the data and methods used to produce it along with an accuracy assessment can be found on github. This is the first statewide estimate of lineament density generated from data at a consistent scale.

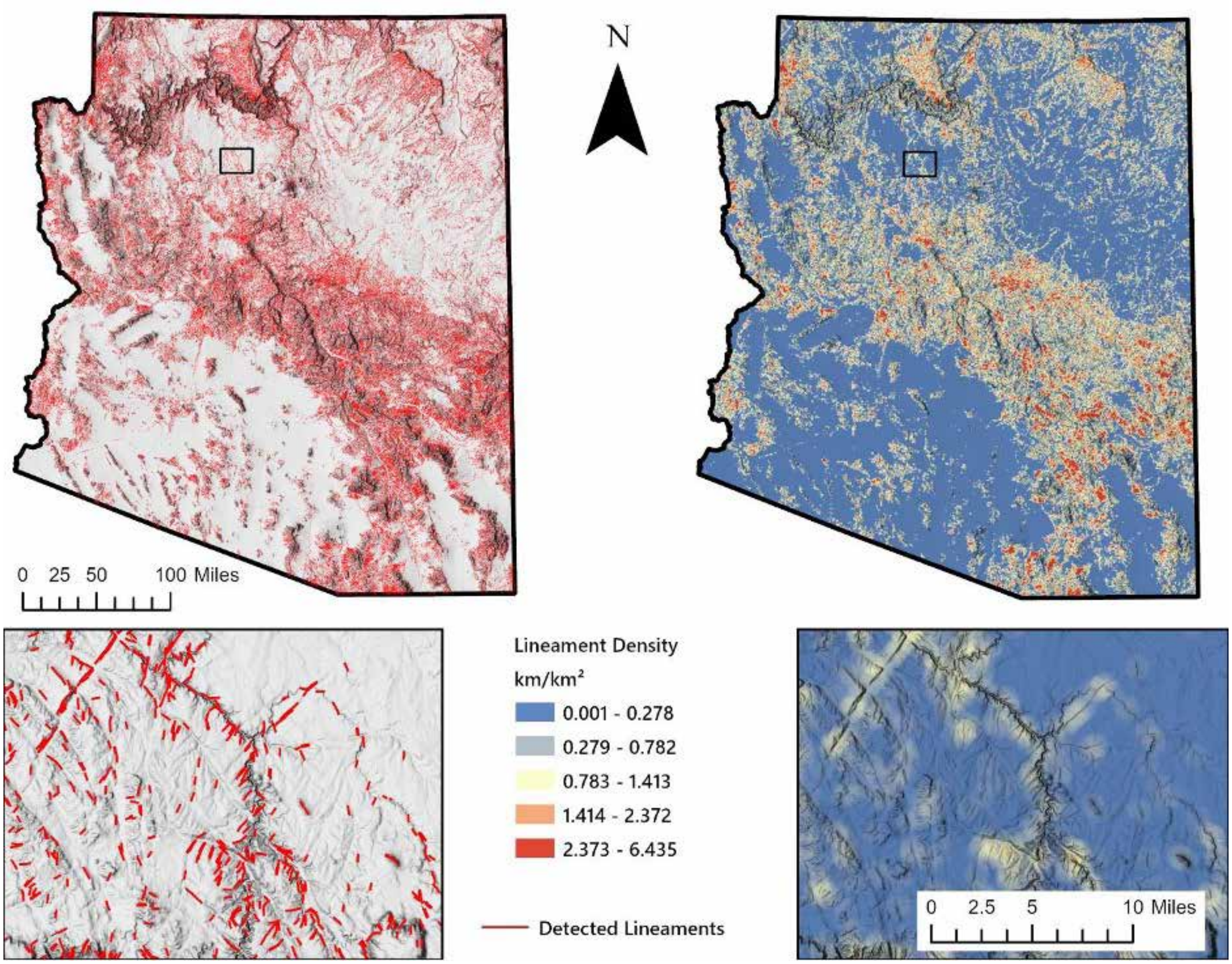


Figure 3.11. Arizona lineaments (left) and lineament density (right). Lineaments were extracted from a multi-directional hillshade derived from the 1/3 ArcSecond (10m) DEM (3DEP) and extracted from the national map using semi-automated methods using the LINE module in Catalyst V3.0.2. Lineament density is the length of lineaments (km) per unit area (km2) and is a widely used thematic layer in suitability studies for zones of enhanced recharge potential. This is the first estimate of lineament density statewide generated from data at a consistent scale. (Source: Lima)

Key Message 3.12:
Controlled tracer experiments in karst systems provide critical empirical data for managed aquifer recharge design in semi-arid regions, revealing rapid subsurface connectivity through structural features that concentrate recharge – these same features render these zones vulnerable to contamination, presenting a fundamental trade-off for system design.

Karst topography represents one of Arizona's most promising yet least understood recharge environments. ATUR investigations have identified focused areas with considerable recharge potential including ephemeral washes, mountain-fronts, and landscapes with karst features (**KM** 3.10 and high incidence of faults and fractures (**KM** 3.11). However, the heterogeneous nature of karst aquifers means that regional-scale models and surface mapping often cannot predict actual subsurface flowpath geometry or transit times at individual recharge sites. Controlled dye-trace experiments provide direct empirical evidence of connectivity and can validate whether promising surface conditions translate to effective aquifer access, all of which is essential information for managed aquifer recharge (MAR) feasibility assessment and regulatory approval.

A pilot dye-trace experiment at Bow and Arrow Wash in Flagstaff (Mroczek et al., in review) demonstrated how tracer studies can characterize recharge behavior in Arizona's karst landscapes. The site exemplifies ATUR-identified high-potential recharge settings: an ephemeral channel incised into fractured Kaibab Formation limestone with documented karst features and structural lineaments intersecting the channel. Prior infiltration testing showed complete loss of 250 gallons per minute within 950 feet of stream channel, confirming rapid surface infiltration capacity typical of well-developed karst. To assess whether this surface infiltration accesses the over 1,000-foot-deep regional Coconino aquifer and evaluate transit times relevant to MAR using reclaimed water, Rhodamine WT dye was introduced under controlled low-flow conditions simulating steady-state MAR infiltration.

Monitoring at downgradient municipal wells revealed tracer arrival to a well 2.7 km northeast after 11–13 days, corresponding to groundwater velocity of approximately 200–250 meters per day. This velocity is characteristic of fractured-carbonate flow regimes where water moves through networks of fractures and bedding-plane partings enhanced by dissolution, rather than through large open conduits or slow matrix diffusion. Critically, the tracer was not detected at another well 5.3 km northeast along the regional gradient, indicating that flowpaths are preferentially directed by local structural features rather than following uniform flow. This pattern is consistent with geophysical evidence that northwest-striking lineaments and horizontal fractures control permeability in the Flagstaff area, demonstrating how karst and structural geology concentrate recharge along specific pathways.

For water managers evaluating MAR opportunities in karst settings, these findings emphasize both the promise and complexity of recharge through ephemeral channels. The rapid 11–13 day transit time confirms the site's capacity to efficiently transmit large recharge volumes and is promising for future recharge enhancement. However, if reclaimed water is used for recharge, the fast velocities and short residence times require care to ensure that aquifer water quality will not be impaired. For such recharge projects, it would be advisable to evaluate the technical and economic feasibility of providing additional treatment to improve the reclaimed water source rather than attempting to determine whether adequate attenuation would take place in the subsurface, which is a very complex scientific challenge. Strategies such as multi-season tracer testing, water quality monitoring using conservative and reactive tracers, and adaptive well management (adjusting pumping rates or temporarily taking specific wells offline during recharge) can help optimize recharge benefits while protecting drinking water supplies.

Summary of Capture and Recharge Strategies Opportunities and Constraints

The ATUR project team has worked to identify and evaluate a broad range of options for capture and recharge in urban, rural, agricultural, and natural landscapes. Opportunities and constraints have been identified for multiple strategies and summarized by landscape type (Urban Areas, Rural and Developing Areas, Agricultural Landscapes, Natural Landscapes, etc.) in Appendix F: Recharge Opportunities Matrix. This summary of strategies was created by collecting ideas from project participants, researchers, partners, and advisors that could be implemented to capture rainwater and/or increase recharge in specific habitats/geological contexts/land use conditions.

For each management strategy, we have identified both key opportunities and major constraints/limiting factors and possible unintended consequences of the options, primarily through expert judgement and experience of team members. Many are ideas that are suitable at small scales (such as GSI-related options), while others may “scale up” to larger landscapes. In some cases, they are strategies primarily used elsewhere in the world. Although there are publications associated with some of these ideas, and specific examples of where they are in use, many are more conceptual in nature. The strategies are organized by the most relevant landscape type, however, strategies may be useful in more than one landscape. Each strategy is denoted with a letter-number code (i.e. A1, D2, etc.) for convenience in referencing. This summary of strategies is also linked by landscape type in the Capture and Recharge Opportunities section of the Decision Support Framework (Section 4, Appendix E).

Natural Landscape Strategies: CCRN

Careful design of recharge projects can help support riparian ecosystems and their services while also enhancing water supplies. For example, the Cochise Conservation and Recharge Network, which oversees multiple projects in the Upper San Pedro watershed, is recharging water to support the regional water supply aquifer as well as the riparian ecosystem. The Network is implementing stormwater control projects that capture excess runoff from urban areas to directly recharge the near-stream aquifer, enhancing habitat suitability for various wildlife species. Rock dams and other structures that capture sediment and runoff can help enhance infiltration and recharge during cooler seasons while also supporting plant growth with retained moisture in warm seasons, providing different benefits throughout the year (Norman et al. 2025, strategy code F2 of the Opportunities and Constraints Matrix).

Opportunistic Recharge Enhancement

Key Message 3.13:
Groundwater supplies can be supported by integrating groundwater recharge considerations into existing land and water management practices. Opportunistic Recharge Enhancement (ORE) is a cross-disciplinary, scalable framework to augment groundwater supplies by strategically integrating recharge co-benefits into existing land and water management practices such as land use planning, forest thinning and stormwater management.

Recharge-related opportunities are commonly missed in the context of land development, and in many cases, land use and land management decisions damage existing natural recharge capacity as well as habitat quality (Gupta et al., 2026). For example, subdivisions are commonly developed to optimize the number of lots within a given parcel, meeting a number of economically-driven objectives. But if areas with high recharge potential were protected prior to platting subdivisions, there would be potential to maximize capture of water that might otherwise have evaporated. Having assessed a wide range of potential applications, the ATUR team has concluded that Opportunistic Recharge Enhancement (ORE) could make a significant difference in enhancing capture and recharge. ORE focuses on strategically integrating recharge co-benefits into land use planning, forest management, road-building and maintenance activities, etc. Applying the ORE approach may be relatively inexpensive in the context of other management actions; in fact, in specific circumstances, significant benefits may be accrued without substantial additional investments. Applying cross-disciplinary insights from ecohydrology and eco-hydrogeology (Cantonati et al. 2020), the ATUR team developed several of these concepts and in the case of changes in forest management, we have calculated the water that could be generated through this approach in suitable ponderosa pine forests in Arizona (see **KM** 3.9).

SECTION 4
DECISION SUPPORT FRAMEWORK

ATUR findings and tools have been integrated into a decision support framework to support Arizona's natural resource managers in achieving their water management objectives through enhanced capture and recharge of rain, snow, and urban runoff. It is a high-level framework with landscape-scale considerations that leaves detailed assessments of recharge suitability to site-specific analyses conducted by the user. Decisions for enhancing groundwater recharge should be made by natural resource managers, in consultation with legal advisors, based on their priorities.

The framework consists of a high-level flow chart and guide (also available as an interactive StoryMap) designed for use by any land or water manager as they consider options for enhancing capture and recharge in their jurisdiction. This framework incorporates consideration of groundwater management objectives, scale and location of the proposed solution, available water sources, recharge threshold criteria, capture and recharge opportunities, and potential costs, benefits, and constraints of possible options. Figure 4 below outlines the ten guiding questions of the framework. The full framework, including a detailed flow chart and guide, can be found in Appendix E.

Capture and Decision Support Framework Steps

1. Water Management Objective
2. Location and Scale of Solution
3. Water Sources Inventory
4. Source Characterization
5. High-Level Threshold Criteria
6. Capture and Recharge Opportunities
7. Suitability Analyses
8. Priority Options
9. Cost/Benefit Analysis
10. Implementation

Figure 4.1. Outline of the ten steps of the Capture and Recharge Decision Support Framework. The full detailed framework can be found in Appendix E.

Potential Partnerships

Recognizing that watersheds and groundwater basins consistently span various management jurisdictions, Step 6 of the framework suggests that the resource manager identify potential partnerships. The potential for new, cross-sector collaborations in managing the state's water resources has been a consistent theme in ATUR's stakeholder engagement efforts. Partnerships can facilitate land use and management decisions and permitting, as well as potential funding options for implementing enhanced capture and recharge strategies. Some opportunities identified in our discussions with stakeholders, Tribes, and resource managers include collaboration with:

- Federal land management agencies, such as the US Forest Service and Bureau of Land Management, to strategically integrate recharge objectives into their ongoing land management practices such as forest thinning, road construction and maintenance, erosion control, and restoration practices;
- Flood Control Districts (FCD) to integrate recharge into flood control objectives though the capture and conveyance of urban enhanced runoff (UER) to areas suitable for groundwater recharge;
- The Arizona Department of Transportation (ADOT) to map potential locations for capture and recharge of road-related enhanced runoff;
- Mining and sand and gravel facilities to incorporate recharge as a part of mine dewatering operations and/or retrofitting existing gravel pits if water quality and hydrogeologic considerations allow;
- Reservoir operators (Salt River Project, Central Arizona Project, municipal and Tribal entities, etc.) to identify and implement strategies for reducing evaporative losses, such as releasing water downstream to recharge facilities; and
- Local watershed groups, conservation organizations, and individual landowners (ranchers, farmers, etc.) in basins experiencing groundwater overdraft to protect and enhance infiltration in areas with high natural recharge potential such as mountain-fronts, ephemeral channels, and regions with underlying karst or fractured geology.

Partnership Opportunities though the Tribal Forest Protection Act

The Tribal Forest Protection Act allows for cross-boundary collaboration between the US Forest Service (USFS) and the San Carlos Apache Tribe (the "Tribe") to co-manage the three National Forests that share a boundary with the Reservation. The Tribe and USFS are working with the US Geological Survey (USGS), nonprofits such as the Taproot Collaborative, and other partners to reduce fire risk through forest thinning and implementing pre- and post-fire restoration techniques that combine Western and Indigenous best scientific practices. Through slowing, detaining, and infiltrating stormwater, these practices, including road shaping to increase water harvesting, installing Natural Infrastructure in Dryland Streams (NIDS, i.e. check dams and beaver dam analogs), and creating fuel breaks through mulching, present opportunities for Opportunistic Recharge Enhancement (ORE) in regions that are hydrologically critical to statewide water resources, such as the Mogollon Rim (Gupta et al., 2026). Enhancing groundwater storage in these high-elevation, forested areas can contribute to increases in downstream baseflow (Norman et al., 2022) for rivers such as the Verde and Salt that supply water to the Phoenix metro area.

Figure 4.2a & b. (a) The San Carlos Apache Tribe Restoration Crew and the Taproot Collective installing erosion control structures as part of a spring restoration project on Mt. Graham in Coronado National Forest, one of the three National Forests that shares a boundary with the Reservation. (b) The San Carlos Apache Tribe Department of Environmental Protection installed NIDS to protect sacred water and springs in partnership with the USGS on the Tribal Land Vegetation and Watershed Modeling project.

4: DSF

SECTION 5
DATA GAPS AND FUTURE RESEARCH

Data Gaps

In the process of conducting this study, a number of data gaps were identified that would support future statewide and localized assessments of capture and recharge opportunities. The most common data gap identified was spatially and temporally consistent observational datasets, such as those developed from in-situ monitoring studies. Examples of monitoring datasets that would improve modeling and representation of water fluxes include a more comprehensive, regularly-measured network of groundwater levels and well pumping rates, more eddy covariance flux towers across different landscapes to support evapotranspiration estimates, and datasets specific to urban environments that can support analysis of stormwater runoff behavior (e.g. surface water modeling results, locations of stormwater management features including drywells and retention/detention ponds). Implementation of additional in-situ instrumentation across Arizona would provide observational data to further evaluate ATUR findings and enhance the potential for increasing water reliability across the state. Specific gaps and suggestions to mitigate them are detailed below:

- **Groundwater-level monitoring remains sparse outside of AMAs**. Additional long-term index wells strategically placed in rural basins could improve understanding of changes in groundwater levels statewide and improve suitability studies. Continuing and increasing ground-based gravity monitoring is useful as a direct measure of the amount of water in the subsurface.
- **Measurement frequency of monitoring wells is often too low to capture short-term dynamics.** There is a need for more frequent groundwater-level measurements and telemetry in rapidly changing or drought sensitive basins.
- **The lack of a statewide requirement for detailed, standardized and fully digitized well logs** and pumping data results in poor characterization of subsurface lithology and aquifer properties. Guidance should be developed for use by well drillers and hydrologic consultants on preparing such well logs.
- **Springs are underutilized as groundwater monitoring indicators.** Springs are an umbrella indicator of the status of recharge over a large area. Monitoring various parameters in a set of carefully chosen, diagnostic springs would greatly improve understanding of the impacts of climate change and human development. Creating a coordinated state-wide spring monitoring network with discharge, temperature, and telemetry would improve our understanding of complex groundwater systems and more effectively monitoring aquifer health.
- **Vertical groundwater gradients are poorly constrained in many basins**, highlighting the need for nested or paired wells to track vertical movement of water, as well as aquifer-system change with depth.

- **Basin geometries are not fully understood and complex hydrogeologic settings such as fractured rock and karst are under-monitored.** Karst landscapes are responsible for a sizeable percentage of base streamflow. The 10 largest springs in Arizona are all karst springs. Targeted wells and spring instrumentation are warranted where current data are sparse, particularly along the Mogollon Rim which is a strategic and important recharge zone within the state. Airborne time-domain electromagnetic (TDEM) studies could be commissioned to characterize basin geometries where they are poorly understood.
- **Public access to data, including real-time data, could be improved.** There are few data sources available using simple online searches for information.
- **Standardization of well metadata is uneven.** Improving metadata could increase the usability of existing databases to meet management and research needs.
- **More robust understanding of the variability in and drivers of atmospheric water loss across the state is needed.** Collaboration and integration with existing flux monitoring networks that measure in-situ ET, such as AmeriFlux, could allow for expansion of the data across Arizona. There is a particular lack of ET data in northern Arizona and in oak-dominated and other mid-elevation woodlands, which cover substantial portions of the state.
- **Methods to measure vertical water flux above the water table are needed** to characterize water flux past the root zone. This remains a major gap that can directly support modeling capacity.
- **Arizona is currently lagging behind other states with sizable karst areas in that it lacks a comprehensive state-wide database of karst features**–including sinkholes, sinking streams, springs, and subsurface connections. The creation of such a database would provide the foundation for effective management, protection, and the sustainable use of water resources in Arizona's karst landscapes.

Future Research

There are a number of avenues in which future research can support continued evaluation of water capture and recharge opportunities to support water management efforts. Research-related recommendations are included below based on hydrologic modeling, stakeholder engagement, and decision support activities.

- **Spatially define areas with supply/demand imbalances:** While groundwater management activities are typically recorded on the groundwater basin scale via net assessments, it is critical to have a spatial understanding of water supply and demand imbalances to manage social and environmental tradeoffs. Future research could include identifying sub-basin scale, spatially explicit areas of potential water (supply) coupled with focused recharge areas near areas of water use (demand).
- **Evaluate groundwater storage/fate of recharged water (aka where can recharge make the most difference?):** Improved hydrogeological understanding of the fate of water that enters into the subsurface, including flow paths and residence time of recharged water, can help optimize recharge locations and strategies and improve policy-relevant estimates.

- **Couple existing groundwater flow models with particle tracking algorithms:** This advancement can allow researchers to delineate subsurface flow paths and estimate travel times from recharge zones to discharge points.

- **Improve evapotranspiration estimates via approaches that link physics-based models with machine learning (ML) approaches:** Initial project results suggest that Penman-Monteith (PM) models can provide a stronger physical basis compared to other models (e.g. Priestley-Taylor), particularly in dry regions where air dryness, soil moisture stress, and rainfall pulses affect ET in complex ways. ML can support, not replace, physics by helping adjust parameters, correct biases, and capture nonlinear responses across climates and land-cover types.

- **Delineate potential source waters (open water, evaporation hot spots) to better define waters available for capture:** This study primarily focused on reducing losses from evapotranspiration (ET), which represents the largest water flux within the natural hydrologic cycle. Separating water that is evaporated directly by the atmosphere from water that is transpired from plants can support targeted assessments of water supply availability and support ecosystem resilience. This is especially important in the drier regions in AZ where ET exceeds P.

- **Develop reliable data for estimation of potential volumes that could be developed from alternative management strategies:** An assessment of tradeoffs, including cost-benefit analyses that include water volumes, are typically required to proceed with water management activities. However, data to conduct these calculations and workflows to develop reliable, scientifically sound estimates are lacking.

- **Develop and compile information on design, performance, monitoring, and maintenance of the drywells and associated detention/retention basins:** Developing quantitative monitoring information alongside coordinated data repositories can support evaluation of strategy performance and the conjunctive benefits of flood mitigation and recharge.

- **Develop information on ways to extend ponding time in detention basins where recharge is desirable:** The importance of ponding time to increasing recharge leads to the conclusion that further research is needed to improve vector control methods.

- **Improve downscaling estimates:** Improving climate downscaling processes, particularly for arid and semi-arid regions, will support estimation and planning for water infrastructure that can support adaptation to a changing climate.

- **Continue work on understanding subsurface hydrology of grasslands and shrublands at the landscape scale:** There is a complex interplay between vegetation, geology, and water availability in these environments that represent critical habitat areas and working landscapes, provision watershed processes, and provide recreation opportunities.

- **Develop communication and translation pathways of scientific findings to support community decisions:** This report and associated products provide a roadmap for enhancing recharge activities across the state, along with a large number of new science findings that are directly relevant to water supply planning within individual groundwater basins or jurisdictions. A strategy is needed for proactively sharing these resources and guiding communities, Tribes, NGOs and private/public interests as they use this information.