ARIZONA TRI-UNIVERSITY RECHARGE AND WATER RELIABILITY PROJECT REPORT

EXECUTIVE SUMMARY

Arizona State University · The University of Arizona · Northern Arizona University

Introduction & Project Approach

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.

In addition, the project team developed foundational hydrological information such as 1) how components of the natural hydrologic cycle (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 dozens of 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). 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 team has held regular meetings with ADWR, the project's Technical Advisory Committee (see Appendix H), and with stakeholders representing a diversity of perspectives and interests that include local, state, Tribal, and federal land and water managers, scientists and NGOs.

Summary of Key Findings

In order to answer the questions that were provided by ADWR related to how and where water could be captured to enhance recharge across the state, it was necessary 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.

Statewide Water Supply Summary

Our investigations of the natural hydrologic cycle across Arizona reinforce prior estimates 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 current natural water balance show that ET exceeds precipitation, indicating a net water loss from the basin. 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 (**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). 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 management areas 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. There are specific 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). 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. 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).

Geographic Information System (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). The ATUR team conducted suitability analyses for flood enhanced recharge (**KM** 3.9), and forest thinning (**KM** 3.8). as well as 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). 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, generating greater quantities of stormwater and opportunities for capture, particularly during winter months (**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).

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. A consistent theme in our discussions with stakeholders, Tribes and resource managers has been the opportunity for potential cross-sector partnerships, because watersheds and groundwater basins consistently span various management jurisdictions. Section 4 of the report includes a list of potential partnerships 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 kilometers (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. 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.

Other model (Noah-MP) simulations used in this study have been evaluated by comparing them with available observations (e.g., evapotranspiration seasonality, snow processes, and runoff patterns). 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.

These datasets are therefore best suited for screening-level analyses and regional prioritization; 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. 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.

ATUR Final Report Key Messages

(Key Contributors & Supporting Information for Key Messages 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