ARIZONA TRI-UNIVERSITY RECHARGE AND WATER RELIABILITY PROJECT REPORT

APPENDIX C: ANNOTATED LITERATURE REVIEWS

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JUNE 2026

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Statewide Water Summary

National Water Model

Summary

1. Introduction and Context

The National Water Model (NWM) is the National Oceanographic and Atmospheric Administration's (NOAA) operational, high-resolution, continental-scale hydrologic modeling system built on the Weather Research and Forecasting Model Hydrological modeling system (WRF-Hydro) framework and primarily using the Noah-MP land surface model. It provides forecasts and analyses of streamflow, soil moisture, snow water equivalent, and other hydrologic variables for ~2.7 million river reaches in CONUS. Since its first operational release in 2016, the NWM has undergone rapid enhancement, including major calibration efforts, expanded data assimilation, improved forcing datasets, and substantial restructuring of model physics. These evolutions reflect the continued need for unified, spatially distributed hydrologic guidance for flood forecasting, drought monitoring, water-resource management, and hazard preparedness.

The literature we provided spans foundational model-development papers, regional applications, model calibration studies, CONUS-scale evaluations, drought-focused performance assessments, and supporting infrastructure (e.g., forcing datasets and routing frameworks). This review synthesizes the main findings across these works to characterize how well the NWM represents key processes, identify systematic limitations that persist, and highlight the directions the community suggests for future advances.

2. Forcing Datasets, Model Architecture, and Core Physics

2.1 Importance of Meteorological Forcing and the AORC Dataset

Several papers emphasize that the quality of meteorological forcing has a strong influence on NWM skill. Fall et al. (2023) describe the Analysis of Record for Calibration (AORC) v1.1, a multi-decadal, ~800 m forcing dataset specifically constructed to support NWM calibration by providing spatially continuous, climatologically constrained precipitation, temperature, radiation, humidity, and wind fields. The paper evaluates bias behavior and shows that while AORC precipitation demonstrates relatively low long-term bias, non-stationarities arise after 2015 due to a lack of climatological constraint, and extreme precipitation events are often difficult to verify—issues relevant for flood-focused NWM applications.

The design and evaluation of AORC underscore a critical message: NWM error characteristics cannot be decoupled from forcing error characteristics. Later performance studies (e.g., Johnson et al., 2023; Hughes et al., 2024) consistently find that hydrologic skill correlates with climate regime and precipitation accuracy.

2.2 WRF-Hydro and Noah-MP Physics

The WRF-Hydro technical documentation outlines the modular architecture, routing options, base flow formulation, channel routing physics, and land–atmosphere couplings that form the computational backbone of the NWM. The system supports multiple surface and subsurface routing formulations, Muskingum-Cunge channel routing, conceptual base flow buckets, and optional reservoir routing. These components interact with the land surface states simulated by Noah-MP, whose structure is detailed in the pair of seminal papers by Niu et al. (2011) and Yang et al. (2011). Together, these establish:

- A multilayer snowpack with improved energy balance and snowmelt representation.
- Dynamic canopy energy balance and multiple vegetation options.
- A groundwater–soil moisture interaction scheme controlling drainage and base flow.
- Multi-parameterization (“MP”) options enabling ensembles and flexible process representations.

These studies demonstrate that Noah-MP improves snow simulation, runoff timing, and representation of deep soil moisture relative to earlier Noah versions. However, challenges remain in representing soil permeability, frozen soil hydrology, vegetation phenology, and groundwater recharge.

3. Process-Specific Findings: Base flow, Snow, Infiltration, and Semiarid Hydrology

3.1 Groundwater and Base flow

Karki et al. (2021) provide one of the first formal evaluations of the NWM’s conceptual base flow module, showing that the bucket-based groundwater representation is not physically explicit, lacks two-way stream–aquifer exchange, and represents groundwater depths unrealistically (with a conceptual storage of 20–250 mm). Using five High Plains catchments, they find:

- Base flow is better simulated in clayey than sandy catchments.
- NWM overestimates base flow during storm events and underestimates it during low-flow conditions.
- Model performance improves when groundwater recharge is reduced using USGS base flow indices.
- A modified Rorabaugh–Rutledge formulation improves the timing and magnitude of base flow.
- These findings confirm that groundwater representation is a structural limitation with substantial regional consequences.

3.2 Channel Transmission Losses and Semiarid Processes

Several studies in semiarid basins (e.g., Viterbo et al. 2020 in the earlier batch; extended here with Mascaro et al. 2023) emphasize the importance of representing channel infiltration and transmission losses. In Arizona’s Oak Creek Basin, Mascaro et al. (2023) conduct a process-based calibration of WRF-Hydro using NWM structure and identify:

- Deep drainage parameterization has a significant influence on winter storm runoff, snowmelt-driven flow, and base flow.
- Summer convective floods are often underestimated due to limitations in rainfall forcing and model structural constraints.
- Spatially variable soil depths and improved representation of slowly varying groundwater stores are needed in mountainous, semiarid environments.
- The study demonstrates the benefits of sequential, mechanism-aware calibration and shows how local parameter modifications improve physical realism.

3.3 Snowpack Biases

Garousi-Nejad & Tarboton (2022) demonstrated that the NWM retrospective snow simulations consistently underestimate snow water equivalent (SWE) and misrepresent melt timing across numerous SNOTEL stations; these issues propagate into streamflow bias in snowmelt-dominated basins. Photogrammetric comparisons and analyses of snow-covered area fraction confirm that temperature and precipitation forcing bias interact with Noah-MP snow physics to produce structural errors.

4. CONUS-Scale Performance Patterns

Two papers provide the most comprehensive national-scale evaluations: Hansen et al. (2019) and Johnson et al. (2023.

4.1 Geographic Variability and Error Attribution

Johnson et al. (2023) evaluate NWM v2.0 streamflow over 4,200 basins and decompose performance into relative skill, conditional bias, and unconditional bias. Key findings include:

- High skill in regions with high precipitation, snow cover, and barren landscapes.
- Low skill in areas with high aridity, strong moisture–energy phase coupling, and extensive forest/grassland.
- Bias patterns:
    - Less bias in wet regions with high precipitation.
    - More bias in urbanized areas and snow-dominated regions.
- Evidence that no single physics configuration performs well everywhere, supporting the move toward NOAA's NextGen heterogeneous modeling framework.
- This is one of the strongest demonstrations that NWM performance limitations are systemic and structurally tied to geographic regime, not just calibration deficiencies.

4.2 Drought and Low-Flow Performance

Hughes et al. (2024) evaluate the retrospective performance of NWM v2.0 in terms of soil moisture and low-flow monitoring for drought detection. Their results show:

- Soil moisture anomalies correlate moderately with in-situ observations, matching the skill of NLDAS-2 land surface models.
- NWM simulated low flows show higher skill for drought identification than does soil moisture.

Operational NWM forcing differs from retrospective forcing, which limits the applicability of real-time drought forecasting.

- Soil moisture transport and deep drainage physics in Noah-MP require revision for drought-focused applications.
- Overall, drought suitability is promising but not yet operationally reliable, especially for flash drought detection.

5. Calibration, Data Assimilation, and the Analysis of Record

5.1 National Calibration Efforts

The NWM v2.1 overview paper (Cosgrove et al. 2024) highlights that improvements in forcing, model physics, routing, and calibration have roughly doubled simulation skill since the 2016 version. Key aspects include:

- Use of AORC v1.1 for nationwide calibration.
- Multi-scale ensemble forecasting (short-, medium-, long-range).
- Expanded data assimilation using streamflow nudging (within channel routing).
- Greater integration with emergency response tools and spatial inundation mapping workflows.

The paper highlights the increasing importance of distributed forecasting and the necessity for consistent, national-scale hydrologic guidance across millions of unmonitored reaches.

5.2 Calibration Frameworks and Process-Based Approaches

Both Mascaro et al. (2023) and the Fall et al. (2023) highlight that calibration must be process-aware and regionally adaptive. The limitations of single-physics nationwide calibration motivate:

- Region-specific hydrologic parameter sets.
- Improved representation of groundwater processes.
- Better multi-objective calibration (streamflow + SWE + soil moisture).
- This aligns with findings from semiarid and snow-dominated regions.

5.3 Data Assimilation and the Role of Nudging

Streamflow nudging in NWM, described in both Cosgrove et al. (2024) and the WRF-Hydro documentation, helps correct states in real time, but its influence decays downstream and is ineffective for hydrologic states like soil moisture. Its benefits are most apparent in:

- Flash-flood monitoring at high-density gauge networks.
- Medium-range forecasts following major events.
- However, many regions lack sufficient gauge density for DA to significantly improve skill.

6. Supporting Datasets and Complementary Modeling Frameworks

6.1 Dayflow CONUS Reanalysis as a Benchmark

Ghimire et al. (2023) describe Dayflow, a VIC–RAPID based 36-year national streamflow reanalysis. They show:

- 49% of sites achieve KGE > 0.5; 58% have |bias| < 20%.
- Assimilating observed flows improves skill, especially in the semiarid West.
- Errors show strong regional patterns tied to hydroclimate and geomorphology.
- Dayflow outperforms NWM and GRADES at many locations in terms of bias and KGE.
- Dayflow serves as a helpful independent reference for evaluating NWM performance and guiding diagnostics.

6.2 Implications for NWM

Comparison to Dayflow indicates that:

- NWM struggles in arid/ephemeral channels where infiltration and groundwater processes dominate.
- NWM routing and soil moisture processes contribute to persistent timing and magnitude biases.
- Ensemble or multi-model frameworks (e.g., NextGen) may improve predictive skill where single-model approaches fail.

7. Synthesis: Strengths, Limitations, and Research Directions

Across these papers, NWM's primary strengths include:

- Nationally consistent, high-resolution hydrologic forecasts and long-term retrospective analyses covering millions of reaches.
- Improved snow, vegetation, and energy balance representation via Noah-MP.
- Rapid operational updates and expanded calibration datasets (AORC).
- Strong utility for flood forecasting, primarily where high-quality forcing exists.
- Reasonable performance for low-flow and drought identification, particularly via streamflow metrics.

Common cross-study challenges include:

- Groundwater and base flow physics are too simplified; they lack two-way exchange and realistic aquifer dynamics.
- Channel infiltration and semiarid hydrology are insufficiently represented.
- Forcing sensitivity remains the largest single source of uncertainty.
- Snow processes, while improved, still show biases in depth, SWE, and melt rate.
- Soil moisture transport and deep drainage schemes limit the skill of drought monitoring.
- No single physics configuration performs well nationally, confirming geographic heterogeneity of hydrologic processes.

Future directions identified in the literature include:

- Regionally heterogeneous modeling strategies (NextGen) for physics tailored to specific processes.
- More flexible calibration frameworks tied to hydrologic regimes.
- Improved soil moisture and groundwater modeling (e.g., deeper aquifer stores, lateral exchanges).
- Greater reliance on ensemble-based and multi-model approaches.
- Enhanced data assimilation beyond streamflow (e.g., SWE, soil moisture, ET).
- Forcing improvements: bias-corrected QPE/QPF, downscaled precipitation, and radar–gauge merger improvements..

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Noah-MP Model

Summary

We used the Noah land surface model with Multiple-Parameterization (Noah-MP) (Niu et al., 2011) to perform hydrological modeling over the 84 8-digit hydrologic unit code (HUC8) basins across Arizona (Qiu et al., 2025). To improve the model realism of infiltration and groundwater recharge, we implemented three key enhancements in soil hydrology (Farmani et al., 2025; Niu et al., 2024; Qiu et al., 2025). First, the model solves the mixed-form Richard's equation, with up to 30 soil layers depending on the bedrock depth and the layer thickness varying from 0.05 m to 10 m from the topsoil to the bottom. Second, the model explicitly predicts surface ponding depth during rainfall events and the infiltration and runoff of the ponded water (infiltration-excess runoff), which is formed when the ponded water in local depressions is connected. Third, the model represents preferential flow through a dual-permeability model, accounting for both slow flow through soil matrixes and rapid flow through macropore networks (or channels). The macropore networks can be formed by abiotic factors (coarse materials, gravels and cracks formed by aggregates during drying-wetting cycles, and ice wedging during freezing-thawing cycles, etc.) and biotic factors (soil organic matter, worm holes, dead roots, etc.). In this study, the fractional volume of soil macropores is simply estimated based on soil organic matter. Further details about the model are available in Niu et al. (2024).

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AMA Models (Prescott)

Summary

The Prescott Active Management Area (PRAMA) groundwater model simulates conditions across the Little Chino and Upper Agua Fria sub-basins from pre-settlement times through 2019, with a partial update in 2021 (ADWR, 2021). To gauge how well the model represents real groundwater discharge, we compared its output against two well-monitored locations: Del Rio Spring and the Upper Agua Fria River at Dewey-Humboldt. At both sites, the model reproduces the general seasonal rhythm and approximate magnitude of flow, but it consistently predicts more groundwater discharge than has actually been measured in recent years. At Del Rio Spring, the model estimates roughly 1,997 AF/yr against an observed 611 AF/yr (1996-2019), and at the Upper Agua Fria River it estimates about 2,385 AF/yr versus an observed 1,689 AF/yr. The match is closer at Del Rio Spring, where the model tracks observed behavior fairly well aside from missing some extremes; performance is weaker along the Agua Fria, where the model smooths over the high variability that characterizes the real base-flow record.

The core issue is that the model's annualized values average across the entire 1939–2019 period, weighting every year equally. Because simulated discharge was higher in the earlier, pre-instrumented decades, this inflates the long-term averages relative to the lower flows observed in recent years. Thus, the model carries a memory of wetter historical conditions that no longer reflect the current regime. For water management purposes, this means that the annualized figures likely overstate today's available discharge. Applying a weighted average that emphasizes recent hydrologic conditions, while still retaining some long-term context, would bring the model's values into better alignment with observed flows and make them more reliable for current and future resource planning.

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AMA Models (Tucson)

Summary

The Tucson Active Management Area groundwater model simulates groundwater flow and storage change across the Tucson basin from roughly 1940 through 2010. Recharge is the dominant input to the basin's water budget and enters the model through four main mechanisms: mountain-front recharge from precipitation infiltrating along the piedmonts (Anderson, 1972; Davidson, 1973; Hanson and Benedict, 1994), channel infiltration along the Santa Cruz River and its tributaries (Schwalen and Shaw, 1957; Condes de la Torre, 1970; Brown, 1976), incidental recharge from sources such as wastewater effluent (Galyean, 1996) and mine tailings (Montgomery and Associates, 2009), and imported Central Arizona Project (CAP) water that is recharged directly into the aquifer (Mason and Bota, 2006). The relative weight of these sources shifts over time: channel and incidental recharge dominate the historical record, while CAP becomes the single largest source between 2005 and 2010 as imported supplies came online. Because the model treats recharge as a prescribed boundary flux rather than a process linked to flow or head, infiltration is assigned as long-term averages, and localized recharge hot spots are generalized into broader zones.

To gauge how well the model represents real conditions, simulated groundwater levels were compared against observed depth-to-water at monitoring wells, with each comparison weighted by measurement reliability. The match is excellent for the steady-state (1940) condition, where 90% of weighted residuals fall within ±10 ft and the mean absolute error is just 4.6 ft. Agreement weakens over the transient simulation, as expected of a long model run: by the final 2010 stress period the mean absolute error grows to 19.3 ft and only 42% of residuals stay within ±10 ft, though 92% remain within ±50 ft. In other words, the model reproduces the broad regional pattern and direction of water-level change reliably, but its accuracy at any single location degrades through time.

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Future Climate Modeling

Summary

We used the Noah-MP model with advanced soil hydrology (Qiu et al., 2025) to simulate hydrological processes in the Colorado River Basin from 1981 to 2099 under the SSP3-7.0 scenario. The Noah-MP model was forced with meteorological variables from the WUS-D3 dataset (S. Rahimi et al., 2024), which provides 9-km dynamically downscaled results of 14 CMIP6 models over the Western United States. In WUS-D3, the climatology of the global climate model (GCM) outputs is bias-corrected prior to the downscaling (Stefan Rahimi et al., 2024). Because the raw precipitation data exhibits large positive biases across the study area, we further corrected precipitation using the quantile delta mapping (QDM) method (Cannon et al., 2015).

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Climate Change and Future Vegetation

Summary

With increased warming, atmospheric dryness, and changing precipitation patterns, it is expected that ecosystems and the vegetation within them will change in response. However, how and when these changes will occur is less certain. This makes it challenging to estimate how vegetation changes might drive changes to Arizona's hydrologic cycle in the future. However, many vegetation changes have already occurred due to episodic disturbances. We can use observed responses from these events to evaluate the potential impacts of further change.

Vegetation change has already occurred: According to Guiterman et al. (2022), high-severity wildfires are the leading cause of vegetation type change in the Southwestern US (AZ, NM, and CO), followed by drought, biotic factors (i.e., bark beetle outbreaks), and land use change. Scientists and land managers in the region who provided accounts of change events identified the conversion of ponderosa pine and other dry forests to shrublands as the most frequent vegetation type change. Forest conversion to shrubland has been associated with a decrease in ET when post-conversion leaf area index (LAI) is lower than that in the forest, leading to potential for increased streamflow. However, the rooting depth (determining water access) and stomatal regulation strategies (i.e., how transpiration responds to drought) of incoming species modulates these effects (Bart et al. 2016). Loss of forest canopy can lead to increased heat loading on the land surface, potentially increasing soil temperatures and soil evaporation, which can lead to water losses and impact the ability of plants to establish and recover the ecosystem (Royer et al. 2011).

Wildfires are expected to increase in severity and kill more trees: In areas where water supply and demand are decoupled (i.e., highest precipitation and supply occur during the cool season when vegetation are less active/dormant), there is much more runoff and potential for enhanced recharge following wildfires. Burned riparian areas have also been associated with periods of increased groundwater recharge (Walvoord et al. 2025).

Water scarcity will continue to limit capture opportunities: In semi-arid to arid regions, ET is largely controlled by precipitation and atmospheric demand for water is high. This leads to lower sensitivity of hydrologic fluxes to changes in land cover, with hydrologic changes dominated by changes in climate (e.g., Dogan and Karpuzcu 2021). This both limits our ability to capture water through vegetation management and the potential to enhance water yield from "unplanned" vegetation changes. Similarly, while less frequent precipitation (and thus more intense, for a fixed annual volume) is associated with higher rates of groundwater recharge (Qiu et al. 2025), this may also increase deep-rooted vegetation cover in dry areas, which can buffer gains in recharge (Liu 2011).

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Base-flow Index

Summary

Base flow is the portion of streamflow sustained between precipitation events primarily by groundwater discharge. Base flow is essential to maintaining perennial river systems, particularly in arid and semi-arid environments where surface runoff is episodic and evapotranspiration (ET) rates are high. Several studies emphasize that base flow reflects a basin's hydroclimatic setting and underlying hydrologic processes. Beck et al. (2013) conducted a global analysis of base flow index (BFI) across over 3,000 catchments and found that BFI is significantly influenced by climate variables (aridity, in particular), soil permeability, and land cover. Arid and semi-arid catchments tend to exhibit lower BFI due to reduced infiltration and groundwater storage, while humid catchments show more sustained base flow contributions. Santhi et al. (2007) applied a digital recursive filter method to estimate base flow across the continental United States and developed regression models for BFI based on watershed attributes such as soil type, slope, land use, and precipitation. Their findings indicate that regional variability in base flow can be systematically linked to physiographic and climatic controls.

Climate change and increasing aridity pose significant threats to base flow sustainability in dryland regions. Ficklin et al. (2016) analyzed trends in stormflow and base flow across the U.S. and found that more arid regions are experiencing significant declines in base flow over time, likely driven by rising temperatures, decreasing snowpack, and declining recharge. These results are also consistent with Ayers et al. (2022), who assessed seasonal and long-term base flow trends and found that warming is most strongly associated with declining base flow during winter and spring, particularly in snow-influenced catchments. The study showed that, in regions where precipitation has declined or shifted seasonally, groundwater contributions to streamflow are becoming more variable. These trends pose risks to ecological stability and water availability in dryland rivers, where base flow serves as a primary source of streamflow during extended dry periods.

Regional studies further highlight the vulnerability of arid region rivers to hydroclimatic stressors. Woodhouse and Udall (2021) focused on the Gila, Salt, and Verde Rivers in the southwestern United States, where warming temperatures and reduced runoff have led to diminishing streamflow reliability. They emphasized that while some variability in streamflow can be attributed to natural climate cycles, anthropogenic climate change is increasing the frequency and severity of droughts thus reducing base flow contributions. These findings underscore the need for improved understanding of base flow dynamics in arid systems. While Beck et al. (2013) and Santhi et al. (2007) provide global and continental-scale context for base flow estimation, the region-specific insights offered by Woodhouse and Udall (2021), Ficklin et al. (2016), and Ayers et al. (2022) demonstrate the compounded effects of warming and drying on already water-limited basins. Collectively, these studies support the conclusion that base flow in arid regions is particularly sensitive to climatic variability, and effective water management strategies must account for these vulnerabilities.

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Strategies for Capture and Recharge

Groundwater Recharge

Summary

Groundwater recharge in arid regions is strongly governed by precipitation dynamics, vegetation cover, and subsurface soil properties. Understanding how these components collectively interact is essential for evaluating recharge feasibility and designing managed recharge systems in water-limited environments.

Chen et al. (2014) used a process-based model (WAVES) to simulate vegetation water-use and recharge across 32 years in a central Australian Acacia savanna. Their results showed that vegetation suppresses recharge in most years, with significant recharge only occurring under wet conditions. A key outcome was the comparison between vegetated and bare land, where bare-soil simulations showed much higher recharge potential, confirming that deep-rooted vegetation drastically limits percolation.

Boas and Mallants (2022) similarly demonstrated that recharge in arid zones is episodic, requiring intense rainfall events (>150–200 mm) to overcome evapotranspiration and storage deficits. Their HYDRUS-1D modeling showed that bare land can recharge at rates up to 157 times higher than vegetated surfaces under the same conditions, further emphasizing the critical role of land cover. They identified antecedent soil moisture and rainfall depth and intensity as the two primary controls on the occurrence and magnitude of recharge in these environments.

Groenendyk et al. (2015) addressed soil controls by showing that standard metrics like Ksat or USDA texture classes poorly capture hydrologic behavior. Through over 1300 HYDRUS-1D simulations, they developed a process-based soil classification that groups soils based on actual water dynamics (e.g., infiltration and drainage behavior). This method allows for improved assessment of recharge potential by identifying how different soil types function under hydrologic forcing, rather than relying on generalized texture-based assumptions.

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Karst Recharge

Summary

Recharge in karst terrains occurs as surface water enters the subsurface through fractures, conduits, and dissolution features, bypassing the slow matrix infiltration typical of porous-media systems. In semi-arid settings, where precipitation is episodic and ET rates are high, recharge tends to be spatially focused along preferential pathways, making the identification of those pathways central to understanding the water balance. Much of the relevant literature concerns mapping the surface features that route recharge. Lineaments, linear features expressing underlying fracture zones, are a key feature, and O’Leary et al. (1976) established the still-standard terminology distinguishing a *lineaments* from *lineation* (internal structural alignment that cannot be mapped as a discrete feature). Aghaee et al. (2021) advanced automated lineament detection with an open-source convolutional neural network trained on topographic, magnetic, and gravity rasters; it performed well within its training area but degraded in dissimilar terrain, indicating that such methods remain limited by training-data diversity. Closed depressions are a second key feature, capturing and concentrating runoff into focused infiltration points. Doctor et al. (2020) developed automated methods to extract closed depressions from DEMs for a preliminary national karst depression density map, while Wall et al. (2015) addressed the false positives that complicate such efforts, improving flow routing and depression detection.

Regional studies in Arizona have linked these recharge features to aquifer-scale water budgets. Parker et al. (2005) synthesized a conceptual model of the Mogollon Rim, finding that recharge is concentrated in a narrow band near the Rim crest. They found that roughly 8 percent of annual precipitation reaches the regional aquifers, with nearly 40 percent of regional recharge derived from leakage of the overlying C-aquifer. Hill and Polyak (2010) characterized Grand Canyon karst as potentially unique among hypogene cave systems worldwide, with discharge pathways continually reorganized by ongoing canyon incision. Donovan et al. (2022) tied recharge timing to snowmelt through hydrograph and isotope analysis of five high-elevation springs, finding that ephemeral conduit- and fracture-dominated systems drain within a month of meteoric input while perennial matrix-block systems sustain discharge for up to nearly 20 months, and that snow *duration*—as opposed to depth or total snowfall—is the statistically significant control on seasonal springflow. Collectively, these studies show that karst recharge in the semi-arid Southwest is spatially concentrated, sensitive to snowmelt timing, and dependent on fracture- and conduit-controlled pathways, underscoring the value of accurately mapping the surface features that govern where and when recharge occurs.

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Playas and Endorheic Basins

Summary

1. Introduction

Endorheic basins, also known as closed basins (or terminal basins) are regions where surface drainage is terminal or landlocked (Wang et al., 2020). They comprise about 1/5 of the earths land area but nearly half of the land area in water stressed regions (Wang et al., 2018). Globally, endorheic basins have experienced significant reductions in total water storage, losing about 106.6 Gt/year of water storage from 2002–2016 (Wang et al., 2018).

Closed basins offer a unique opportunity in the Western U.S. because generally all water in these basins is either evaporated, transpired, or recharged to groundwater. Seldom is water from these arid closed basins exported. While water rights claims may exist within these basins, changes to the water balance will not affect water rights in the Colorado River or its tributaries, so reductions in water use or evaporation can be recharged without affecting water rights in the Colorado River system. In Arizona, endorheic basins cover approximately 43,400 square kilometers, or about 15% of its land area. This literature review aimed to identify opportunities to enhance groundwater recharge, which might be applicable in Arizona's endorheic basins.

2. Playas

Playas are topographic low points within closed dryland catchments (McKenna and Sala, 2018). They are typically shallow, circular depressions with clay-lined floors. Playas often form ephemeral or temporary lakes or wetlands and are important wetland habitats, particularly for migratory birds (Frus et al., 2025. We found 301 playas in Arizona by querying the National Hydrologic Dataset (NHD) covering a combined area of about 221 square kilometers.

For a long time, it was assumed that very little recharge occurs through playas, due to their clay-rich floors, and it was assumed that all water flowing into these playas would be lost to evaporation. One study found that a 100 acre playa in Texas would lose an average of 600 gallons a minute to evaporation during July (Valliant 1975). However, studies examining recharge rates beneath playas on the high plains overlying the Ogallala aquifer found that recharge rates ranged from 0.01 inches per year up to and exceeding 10 inches per year and exceeded recharge rates in the area surrounding inter-playa areas (Gaurdak and Roe 2009). In the more arid Jornada Basin near Las Cruces, NM, recharge rates were estimated, and they found that recharge occurred under all 15 sampled playas with an average recharge of 6mm per year or 2% of annual rainfall in the study area (McKenna and Sala, 2018). The New Mexico Study suggested that increased rainfall variability with climate change may enhance playa recharge rates despite reductions in average annual rainfall, because only the largest rainfall events produced runoff, which inundated the playas. One proposed causal mechanism for enhanced recharge through playa floors is that during dry periods, the clay-rich floors crack, allowing water to percolate through the cracks and recharge the underlying aquifer (Guardak and Roe 2009). However, an analysis by the Texas Water Development Board found that while cracks in playa floors led to enhanced infiltration, most of that water is stored in the top 3 meters of soil beneath the playa and is still subject to evaporation (Weinberg et al., 2021).

The largest playa in Arizona is the Willcox playa in the Sulphur Spring Valley of Southeastern Arizona, covering an area of about 126 Square kilometers, followed by Red Lake Playa in the Hualapai Valley of northwestern Arizona, covering an area of about 54 square kilometers. Groundwater levels in the basins below both playas have been in decline due to groundwater use for irrigation (Knight et al., 2021; Scanlon et al., 2025). In the Willcox basin, 20–50m declines in groundwater level have been observed, and as a result, the ground has subsided up to 3 meters during the last 65 years (Scanlon et al., 2025).

3. Enhancing Recharge

Guardak and Roe (2009) review several studies in the high plains that examined the potential for enhancing groundwater recharge through playas. These attempts included drywells, pressurized injection wells, removing the top clay layers from playas, creating deeper pools with less surface area, and by installing geotextiles beneath playas. (Guardak and Roe 2009). The suspended silt in the playa water caused issues with dry wells, which clogged quickly with fine sediment. Geotextiles were found to be effective at filtering out some of the suspended sediment but required annual maintenance. Removing the top layer from the bottom of playas was found to be effective in the short term, but the clay layer would reform over time, reducing the effectiveness of this method. Pressurized injection wells were found to be effective at enhancing recharge but were energy-intensive to operate (Urban, Clayborn, and Ramsey, 1998; Guardak and Roe, 2009).

Other studies have focused on capturing water before it reaches playas and diverting it to managed aquifer recharge projects (Salameh et al., 2019). Hillslopes in the mountain fronts of these watersheds offer tremendous potential for capturing and recharging water, and roads on hillslopes have been proposed as an interface for capturing runoff (Meles et al., 2024).

One promising technique for enhancing recharge before runoff reaches the playa was tried by Norman and others (2025) within the Willcox basin. They created leaky weirs and check dams in ephemeral streams within the mountain front. These structures slow the flow of water, retain sediment, increase water residence time by recharging shallow alluvial aquifers, and show evidence that new water was mixing with older water and may be recharging deeper aquifers.

A detailed site analysis should be completed before implementing any of these techniques in endorheic basins in Arizona. Playas in Arizona are likely different than playas in the high plains and the Jornada basin, so techniques that were effective in those regions may not be effective in Arizona. The Willcox playa is a good candidate for further study because it is the largest playa in Arizona and has experienced significant groundwater declines. However, modifications to playas or attempts to intercept water before it reaches playas may have unintended consequences for the ecology of these important wetland habitats. Because most endorheic basins in Arizona are arid, there is less opportunity to reduce evaporation through vegetation management. However, there are some endorheic basins, such as Mormon Lake, which are forested and may benefit from thinning or other vegetation management techniques to reduce ET and enhance the portion of water available for recharge.

Though not technically endorheic, many areas of Arizona are underlain by karst aquifers and exhibit significant internal drainage, which may offer many of the same opportunities as endorheic basins; however, more work needs to be done to delineate these areas and quantify their potential for groundwater recharge.

See related datasets: AZPlayasSinksClosedBasins_AGOL

Steps for processing: AZ Playas and Endorheic Basins Github

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Focused vs. Diffuse Recharge

Summary

Groundwater recharge occurs through two primary regimes: diffuse recharge, which involves broad, low-intensity infiltration across the landscape, and focused recharge, which occurs through localized pathways such as stream channels, fractures, or sinkholes. In arid and semi-arid environments, focused recharge is often the dominant process due to the spatial and temporal variability of precipitation and the high evaporative losses from bare soils. Goodrich et al. (2018) demonstrated that in the San Pedro watershed of the southwestern U.S., monsoon-driven ephemeral streamflow plays a crucial role in generating focused recharge through channel losses, highlighting the importance of storm-driven runoff events for recharge. Similarly, Ajami et al. (2012) used a Normalized Seasonal Wetness Index to show that focused recharge from mountain front systems significantly contributes to aquifer replenishment in semi-arid catchments of the Upper San Pedro Basin.

In contrast, diffuse recharge tends to be more sensitive to long-term climatic trends and land surface conditions. Small (2005) analyzed arid zones in the southwestern U.S. and found that diffuse recharge is generally minimal, with thresholds for annual precipitation and potential evapotranspiration that must be exceeded for recharge to occur. This aligns with findings from Deng et al. (2015), who used chloride mass balance methods in northwestern China to show that diffuse recharge decreases with increasing aridity and is more responsive to interannual climate variability. West et al. (2022), examining African aquifers, also highlighted the significant control exerted by precipitation intensity, soil properties, and vegetation on whether recharge occurs via diffuse or focused pathways. Together, these studies underscore the fact that while both recharge regimes are present in arid systems, focused recharge, typically through episodic and extreme precipitation events, is the dominant and more reliable contributor to groundwater replenishment in water-limited regions.

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Floodwater Recharge

Summary

Aquifer recharge using flood waters is an established way of mitigating potential damage from excess surface water and providing environmental and ecosystem services by recharging groundwater for later use. Aquifer recharge can be active, through such means as injection wells, or passive, such as in the case of Hashemi, et al. (2015) in Iran. Through use of a passively managed floodwater spreading system, they were able to demonstrate effective groundwater recharge from diverted flood waters, although their achieved recharge rate was approximately 1/3 of inflow, on average, and was highly variable due to seasonal and other poorly understood factors.

Understanding where conditions are suitable for flood enhanced aquifer recharge is a challenge. There are two general criteria, first there must be periodically available flood waters, and second there must be suitable subsurface conditions for infiltration and recharge. These conditions are often estimated using available datasets through a process of multicriterion decision making (MCDM) and analytical hierarchy process (AHP), also known as suitability mapping (Aloui et al., 2024; Saaty, 1984). Mudashiru et al. (2021) has documented the rapid rise in the number of publications utilizing MCDM and AHP methods for flood hazard mapping in recent years, and cites many applicable case studies. However, these methods are often highly subjective, relying heavily on the factors considered and the weights ascribed to each factor. These methods require expert analysis and are not easily validated.

Alternate methods for assessing flood water hazards include machine learning (ML) techniques, such as decision tree and random forest algorithms. Although less popular than suitability mapping, these ML methods have also been increasingly cited in literature in recent years (Mudashiru et al., 2021). For example, Tehrany et al. (2019) demonstrated that a decision tree ML approach was highly effective at mapping flooding on the Brisbane River in Australia using only topography derived data (data directly derived from a digital elevation model). Due to the wide availability of topography data, these models can be trained and validated using existing flood data and applied broadly across large areas with little available data with a relatively high degree of confidence. Additionally, while these methods do require a technical GIS and ML skillset, they do not rely on expert hydrologic analysis, or subjective weighting schemas (Tehrany et al., 2019).

Additional sources of flood water include ephemeral water bodies within internally draining watersheds (i.e. playas). While many playas have been well mapped within Arizona, there is limited data available regarding the volume of water which flows onto them (and subsequently the volume of water lost to evaporation). A variety of remote sensing methods have been investigated to try to estimate this volume of water (e.g. Tran et al., 2022), however the success of these methods has been limited, and further study is required. Ultimately quantification of these ephemeral waterbodies may not be necessary. Due to their known locations and history of flooding, methods to enhance aquifer recharge may be applied either by diverting or slowing flood waters before they reach impermeable areas, or by opening pathways through the impermeable layers of the playa. Quantitative estimates can be developed using traditional hydrological survey methods.

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Hillslope and Road Managed Aquifer Recharge

Summary

Hillslopes in the mountain block and mountain front often account for much of the recharge to valley floors or adjacent basin-fill aquifers (Bouimouass et al., 2020;Wilson and Guan, 2004; Schreiner-McGraw and Ajami 2022) ; however relatively little has been done to explore opportunities to enhance recharge along roads on hillslopes in the mountain fronts (Meles et al., 2024). Mountain block recharge (MBR) is the flow of groundwater to basin aquifers from adjacent mountain blocks. Mountain Front Recharge, (MFR) is recharge that occurs in the contact zone between the mountain block and the adjacent valley fill (Markovich et al., 2019; Wilson and Guan 2004). Meles and others (2024) explores the possibility of using existing road infrastructure to capture and convey recharge to suitable areas within the mountain front. Despite MFR and MBR being a major component of recharge to basin fill aquifers but is often difficult to quantify and characterize due to limited hydrogeologic data, in mountain blocks and at the mountain fronts (Markovich et al., 2019). Recharge capacity within the mountain blocks and mountain fronts is largely dependent on climatic conditions and geologic controls, the rock type (primary permeability and porosity) and the degree of fracturing or weathering (Stonestrom and Harrill, 2007). Identifying alluvial fans in mountain front zones, particularly those with high infiltration capacity could help map suitability for hillslope recharge. Bowen and others (2014) utilized thematic layers of slope and land cover to identify mountain front areas using GIS.

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Thinning / High-Elevation Forest Recharge

Summary

Up to 60% of precipitation in Arizona's high-elevation forests occurs during winter in the form of snowfall (> 1,800m) with moisture sourced primarily from large pacific storms (Baker 2013). Isotopic analysis of groundwater confirms that recharge in northern arizona and other high-elevation areas throughout the state, are dominated by snowmelt and winter precipitation originating from pacific frontal systems (Eastoe, 2023; Eastoe and Towne 2018; Earman 2005). High-elevation recharge from forests on the Colorado Plateau and Mogollon rim provide significant recharge to both regional aquifers and nearby basin-fill aquifers (Eastoe and Wright 2019; Parker et al 2005). Regional groundwater in Northern Arizona is a mix of older, deeper groundwater and young groundwater from snowmelt (Springer et al., 2017; Eastoe 2007). Isotopic analysis of groundwater also confirms that mountain-front and mountain block recharge in the Verde valley is dominated by water from relatively small high-elevation areas in each of its subbasins (Blasch et al., 2006). The volume of groundwater issuing from springs along the Mogollon Rim and Kaibab plateau and the duration of its flow had a strong relationship with snow persistence and duration (Donovan et al., 2022).

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Snow Management

Summary

In Arizona, snow is an important driver of the hydrologic cycle. It can account for over half of annual precipitation at the highest elevations, and contributes significantly to water supply, recharge, and ecosystem health. Because of its importance, alterations to snowpack, either through climate or land cover change, could have profound hydrological consequences.

Arizona's snowpacks are often found in mountain forests, which are affected by a variety of natural disturbances such as forest fire and insect infestation, as well as forest restoration efforts aimed at reversing the effects of decades of fire suppression. While there has been significant work to understand hydrologic effects of forest disturbance, there is still no generalized understanding of the hydrologic implications of forest management practices, such as mechanical forest thinning or prescribed burning (Goeking and Tarboton, 2020). A given reduction in canopy cover can be associated with a variety of snowpack responses, depending in part upon the spatial arrangement of trees. The spatial arrangement of trees is often an important determinant of snowpack depth and longevity due to its effects on shortwave and longwave radiation, wind speeds, and turbulent fluxes (Musselman et al., 2012). This leads to a complex interplay between areas with more or less snow accumulation (i.e. increases in SWE) vs. those with faster or slower snow ablation (i.e. decreases in SWE), causing complex patterns of maxima and minima in snowpack amount, duration, and liquid water input (rainfall + meltwater leaving the snowpack) in different forest environments (Dwivedi et al., 2024).

Due to the impact of canopy on snowpack, deliberate forest management (e.g. forest thinning) can impact the amount and timing of snowmelt and snow that is lost to sublimation. Generally, a reduction of canopy cover increases liquid water input because of a reduction of interception and subsequent sublimation, though this is balanced in some cases by a loss of shading, which can cause more snowpack sublimation and mid-winter ablation (Harpold et al., 2014). In the southwestern US, canopy cover between 25% and 40% appears optimal for net snow accumulation at continental mid-latitude sites (Veatch et al. 2009, Donager et al. 2021), though this is dependent on elevation and aspect, with lower forest densities being optimal for areas with shorter snowpack duration (such as lower elevations) and higher forest densities being optimal for areas with longer snowpack duration (Broxton et al., 2020). Generally, lower forest densities allow more snow to fall to the forest floor but also decrease shading and allow for earlier snow disappearance (Varhola et al., 2010).

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Riparian Management and Recharge

Summary

In Arizona, riparian (riverbank) areas have higher vegetation cover, water availability, and evapotranspiration (ET) relative to the uplands, where water tables are well beyond the rooting zone of plants (Fan et al. 2017). Especially in the hotter, more arid southern and low elevation parts of the state, evapotranspiration in riparian areas can be up to double precipitation on an annual basis (Scott et al. 2008). This is possible due to convergence of groundwater in these near-stream zones becoming base flow and a source of transpiration for trees, shrubs, grasses, and other riparian plants (Gallo et al. 2024; Bromley et al. 2026). Because riparian and deep-rooted vegetation can have relatively high rates of transpiration, there has long been interest in how management of these ecosystems can affect atmospheric water losses.

The most abundant non-native riparian woody plant in the Southwest is tamarisk, AKA saltcedar (species in the genus Tamarix). Originally introduced for erosion control, it is now widespread in the region, partially due to declining water availability in riparian zones (Glenn and Nagler 2005;

Stromberg, Lite, and Paradzick 2005). Tamarisk has comparable transpiration rates to native riparian vegetation (e.g. cottonwood and willow) in high quality wetland areas with near-surface groundwater (Palmquist et al. 2026) but also exhibits higher drought and salinity tolerance. Declining soil moisture and groundwater levels results in reductions in water use and, if the changes are extreme enough, mortality of native riparian trees; when these plants are replaced by tamarisk, the ecosystem's water demands remain high (Glenn and Nagler 2005; Hultine and Bush 2011). Management of tamarisk may have the highest potential to reduce ET in areas where water availability has declined and native vegetation with lower water demands can be effectively established (Palmquist et al. 2026). Even so, studies have not thus far shown tamarisk removal to reliably result in increased groundwater availability (Shafroth et al. 2010; Doody et al. 2011).

Defoliation of tamarisk can result to temporary reductions in ET. The tamarisk leaf beetle (species in the genus Diorhabda) feeds exclusively on the leaves of tamarisk trees and was introduced to the United States to attempt to reduce tamarisk leaf area and thus transpiration. While defoliation by the beetle has been shown to reduce ET for up to 1-3 years, ET rates can eventually recover as the tamarisk regrows (Nagler et al. 2012; Snyder and Scott 2020). Even where reduced ET following management has been observed, tamarisk removal has not been decisively linked to increases in streamflow or groundwater storage.

Apart from direct vegetation management, one strategy with pronounced co-benefits for recharge and riparian ecosystems is the use of rock detention structures (RDS). RDS can enhance infiltration, base flow duration, and groundwater recharge while also preventing further stream incision and dewatering (Norman et al. 2016). These structures enhance and restore riparian ecosystems through accumulation of sediment that can store water and support plants (Norman et al. 2025). By increasing the abundance and density of wetland vegetation, RDS further support wildlife habitat and biodiversity (Norman et al. 2022).

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Rangeland Management and Recharge

Summary

Rangelands in Arizona are comprised of several million acres of grasslands, woodlands, shrublands, and savannas, encompassing a range of vegetation types. These ecosystems are semi-arid, with potential evapotranspiration exceeding precipitation on an annual basis. The high evaporative demand in these areas makes capture of water that would be lost to the atmosphere difficult, but there are many land management strategies that can enhance the potential for groundwater recharge while simultaneously supporting ecological integrity and function.

Many areas in Arizona have undergone woody plant encroachment (WPE), or an increase in the density of shrubs and trees accompanied by a loss of herbaceous and grassy plants on large landscape scales (Archer et al. 2017). Modeling studies have shown that mesquite (Prosopis velutina) encroachment may reduce groundwater recharge because of increased use of deep soil moisture for transpiration (Nie et al. 2012). However, in upland settings (with deep water tables), there are no notable differences in the proportion of incoming precipitation (P) that is partitioned to evapotranspiration (ET) between shrub- and grass-dominated sites in southeastern Arizona (Scott 2010); in fact, some rangelands sparsely vegetated by creosote may have lower ET to P ratios than nearby grasslands (Glenn et al. 2015). WPE is usually associated with an increase in bare ground cover, which can increase runoff from mesquite shrublands (Pierini et al. 2014) and sagebrush shrublands (Pierson et al. 2010), potentially enhancing water available for capture in stream channels through transmission losses that recharge local and then regional aquifers (Goodrich et al. 2004).

Field studies in the Great Basin looking at the effects of removing encroaching trees from shrublands have found that thinning these species increases soil water content and plant-available moisture, but that non-native flammable grasses can quickly establish (Roundy et al. 2014). Pierson et al. (2010) also found that leaf litter helped enhance infiltration and store rainfall, suggesting that vegetation management that incorporates mulching and/or uses native materials as ground cover could enhance hydrologic stability following treatments. Finally, some studies in karst rangelands have shown that WPE can increase conductivity of rock substrates through enhanced weathering (Leite et al. 2023), which could lead to large increases in diffuse recharge on landscape scales.

These results highlight how changes in precipitation partitioning and soil moisture trends in moisture-limited rangelands may not have substantial implications for recharge, since many other processes compete for available moisture. However, rangeland management can influence recharge potential particularly through managing for increased infiltration.

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Modeling on Forest Thinning

Summary

Forest thinning is a commonly employed silvicultural practice to reduce wildfire risk (Stephens et al., 2009; Taylor et al., 2021), improve forest health (DeMaynadier & Hunter, 1995; Kang et al., 2014), and potentially enhance water yield (Sun et al., 2015). Beyond these ecological and management objectives, thinning alters forest structure in ways that directly affect the movement and partitioning of water within a catchment. This intervention can significantly influence catchment-scale runoff dynamics by altering key hydrological processes. Specifically, thinning can reduce canopy interception, lower evapotranspiration (ET), and increase throughfall (Dung et al., 2012; Schenk et al., 2020; Del Campo et al., 2022). However, these effects vary with forest type, climate, thinning intensity, and are further influenced by spatial and temporal scales of observation (Del Campo et al., 2022). Over the past two decades, modeling efforts have become essential tools to understand and predict the complex hydrological responses to thinning across diverse climatic, topographic, and forest conditions.

A variety of models have been employed to simulate forest thinning impacts on hydrology, ranging from empirical statistical approaches to process-based models (Komatsu & Kume, 2020; Sun et al., 2023). Leaf area index (LAI) is often used as a key vegetation parameter linking structural changes from thinning to hydrological processes (Sun et al., 2011). For example, Sun et al. (2015) used the WaSSI model to simulate water yield sensitivity to LAI changes across ~2100 basins in the conterminous US, showing that reductions in LAI generally increase water yield, but the magnitude of change depends strongly on precipitation regime and temperature patterns.

Paired-catchment modeling and field observation studies consistently show that thinning reduces evapotranspiration and interception losses, leading to increases in base flow and total runoff (Dung et al., 2012; Del Campo et al., 2022). However, the magnitude of modeled runoff increases is highly sensitive to thinning intensity and the representation of soil–vegetation–atmosphere feedbacks. For instance, in Japanese cypress catchments, Dung et al. (2012) applied pre and post thinning monitoring alongside a distributed model to show that a 43% basal area removal increased annual runoff by ~240 mm, primarily through delayed runoff rather than quick storm runoff. These findings highlight the need for process-based representation of hydrological components in model frameworks.

Process-based ecohydrological models such as RHESSys, tRIBS, and TOPMODEL, have been applied to quantify changes in water balance components and to evaluate management scenarios under different climatic and vegetation conditions (Sun et al., 2015). In the Sierra Nevada, Saksa et al. (2017) applied the spatially calibrated RHESSys model, which integrates vegetation, soil, and climate interactions, to assess the effects of low intensity of thinning. Their results showed that thinning increased mean annual runoff by 14% in wetter central Sierra but had negligible effects in the drier southern Sierra, reflecting the strong control of climate on thinning effects on hydrological responses. Similarly, Moreno et al. (2016) used the physically based distributed tRIBS model in semi-arid basins of the southwestern United States to evaluate long-term water balance changes following thinning. They found that reductions in evapotranspiration translated into water yield gains, but only where precipitation inputs and soil water storage capacity were sufficient to sustain these increases. Complementing these findings, Momiyama et al. (2021) applied the TOPMODEL framework to assess forest thinning during hydrological drought periods in Japanese catchments. Their simulations indicated that while thinning could improve low-flow conditions in wetter years, its benefits during severe droughts were limited unless catchments had high water retention capacity.

While these surface-focused modeling approaches provide critical insights into runoff generation and evapotranspiration dynamics, they do not fully capture how thinning influences subsurface water movement and storage. Groundwater-linked hydrological modeling further extends this understanding to subsurface processes. Wyatt et al. (2015) used a regional groundwater flow model coupled with recharge-change factors derived from forest basal area reductions to estimate a 2.8% recharge increase to the Verde Valley subbasin following large-scale ponderosa pine thinning. However, they also highlighted rapid attenuation of these gains due to post-treatment vegetation regrowth and competing water demands.

Overall, these modeling efforts reveal that while the direction of hydrological change from thinning is generally consistent, with reductions in ET and interception leading to increased runoff or recharge, the magnitude and partitioning of these changes depend on climate regime, forest type, thinning intensity, and temporal scale of analysis (Zhang et al., 2017; Sun et al., 2023). This underscores the importance of using suitable process-based models which can represent coupled energy–water–vegetation dynamics to better understand and predict the hydrologic effects of forest thinning.

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Hydrologic Response of In-Stream Structures

Summary

Natural and engineered methods to enhance recharge in arid and semi-arid regions have been explored given the demand for sustainable water management in these water-scarce areas (Fandel, 2016; Nichols et al, 2016; Norman et al, 2017; Lucas-Borja et al, 2021; Hseih; 2022). Rock dam structures (RDS), such as check dams and gabions, are commonly used in ephemeral streams to enhance water retention. These structures function by slowing runoff, increasing water retention time, and expanding the ponded surface area. By increasing the ponding area and prolonging water presence, these structures facilitate greater infiltration into the soil (Fandel, 2016, Norman et al, 2016). This process can facilitate the recharge of aquifers through deep percolation, improving both soil moisture in the vadose zone and the availability of water for plant uptake.

The benefits of RDS extend beyond subsurface infiltration. By enhancing water availability beneath the structures, they support vegetation growth through increased root-zone moisture, leading to improvements in vegetation cover and ecosystem greenness. The retained water may also contribute to enhanced base flow in downstream channels, supporting streamflow especially during the dry seasons. Studies conducted in the southern regions of Arizona support the efficacy of RDS, reporting increases in vegetation density, soil moisture, and sustained base flow in ephemeral streams where RDS were introduced (Norman et al, 2016; Norman et al 2019; Gooden and Pritzlaff, 2021; Wilson and Norman, 2023).

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Post-Fire Hydrologic Response

Summary

Wildfires have significant impact on the hydrologic cycle in arid and semi-arid regions, impacting surface flows, evapotranspiration (ET), and groundwater recharge. 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 often lead to increased runoff and streamflow volumes in burned areas but diminishes groundwater recharge locally (Hallema et al, 2017; Moussoulis et al, 2015; Folador et al, 2021). Simultaneously, wildfires reduce ET by eliminating vegetation, which directly lowers transpiration losses and increases water 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.

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Existing Urban Stormwater Runoff / Recharge

Summary

Urbanization fundamentally alters local hydrology by replacing permeable soils with impervious surfaces, a process that simultaneously exacerbates flood risks and diminishes natural groundwater recharge (Shuster et al., 2005). Traditionally, this excess runoff is viewed as a nuisance to be evacuated rapidly. However, facing dual pressures of aquifer depletion and climate variability, stormwater is increasingly recognized as a critical, underutilized asset for water supply resilience (Luthy et al., 2019; Scanlon et al., 2023).

To manage stormwater and mitigate flooding, cities have widely adopted Green Stormwater Infrastructure (GSI) and Low Impact Development (LID) such as retention ponds, rain gardens, and permeable pavements (Dietz, 2007). While terminology and specific applications vary globally, the consensus remains that GSI effectively mitigates peak flows while offering co-benefits such as urban heat island reduction (Fletcher et al., 2015). Nevertheless, the adoption of these systems is often uneven, shaped significantly by local regulatory frameworks and socio-political factors, as seen in comparative analyses of cities like Portland, Baltimore, and Phoenix (McPhillips & Matsler, 2018).

In arid or space-constrained urban environments, however, surface-based GSI may be limited by high evaporation loss and land scarcity. Here, “grey” infrastructure solutions, particularly drywells, offer an alternative. Research indicates that drywells can bypass near-surface evaporation and effectively transmit runoff to deep aquifers, provided proper siting and maintenance (Edwards et al., 2016). Furthermore, modeling studies suggests that drywells can outperform larger surface infiltration basins in both recharge efficiency and land-use economy (Sasidharan et al., 2021).

Quantifying the potential of stormwater runoff capture for groundwater recharge enhancement is essential for water resource planning. Early site-specific studies in Chandler, Arizona, demonstrated that engineered retention systems could capture nearly all local runoff, turning a negligible natural recharge rate into a significant water resource (Milczarek et al., 2005). Building on this, recent metropolitan-scale assessments using remote sensing have confirmed that existing infrastructure captures substantial runoff volumes in metropolitan Phoenix, with future urbanization projected to further increase this harvestable resource if properly managed (Su et al., 2025).

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Green Stormwater Infrastructure

Summary

While green infrastructure (GI) for stormwater capture is popular in wet regions, not much research has been conducted in semi-arid and arid regions. Several methods of green infrastructure, including rain harvesting systems, rock detention structures, and retention basins, can be used to capture stormwater. In the High School watershed in Tucson, the Automated Watershed Assessment (AGWA) tool and KINEROS2 tool were used to model small-scale runoff flows (Korgaonkar et al. 2021). By increasing GI by two (using retention basins, roof runoff harvesting, and traffic chicanes), peak flows would be reduced by 7.3%, and if GI was increased by five times, peak flows would decrease by 22%; these reductions would support landscape irrigation demands. While these are effective ways to capture runoff from events, retention basins can greatly reduce runoff volume by up to 30% compared to other implemented GI (Korgaonkar et al. 2018).

Similarly, utilizing rock detention structures (RDS) can also reduce peak flow events and increase infiltration. In Mountain Park, Phoenix, Arizona, RDS were found to increase infiltration by 15% (Norman et al., 2016). GI can also be interchanged with low impact development (LID). In the Woodcutter Wash watershed in Sierra Vista, AZ, LID models showed a decrease in peak flows of 3.5%, while in Bella Vista, they could decrease by 12% (A Stormwater Action Plan for Sierra Vista, 2016). Expanding further than the western United States, a study in Larkana, Pakistan, which is a warm desert climate, installed a 20 m3 rainwater harvesting system (RHS) which achieved a 33% water saving, and captured 61% of stormwater (Ali et al., 2020). These studies all yield similar results: that GI/LID can reduce peak flows while continuing to capture stormwater in various ways, likely leading to an increase in infiltration.

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New Urban Development Runoff / Recharge

Summary

A growing body of research has investigated the hydrologic impacts of projected land cover change, particularly its influence on surface runoff in urbanizing areas. Kepner et al. (2004) conducted one of the earliest peer-reviewed scenario analyses, linking future land use to hydrologic outcomes in the San Pedro Watershed, Arizona. Here, researchers find that all modeled scenarios led to increased runoff in the simulation period 2000 to 2020, with the most expansive urban growth scenario producing the greatest change in runoff compared to baseline 2000 conditions. Building on this work, Kepner et al (2016) utilized ICLUS land cover projections to evaluate hydrologic response from 2010 to 2100, also showing high growth scenarios notably increased human land use and runoff—especially at the sub-basin scale. Expanding outward to a global context, Ju et al. (2023) analyzed the Beijing-Tianjin-Hebei region in Northern China and demonstrated that urban expansion and climate change together amplify runoff, with urban growth driving short-term changes and climate change exerting more influence over the long-term.These studies collectively highlight the importance of integrating land use projections and climate scenarios in modeling frameworks, to capture the spatially variable and scale-dependent nature of runoff generation under future development trajectories.

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Urban Frameworks (Modeling Boundary Conditions)

Summary

While physical process-based models such as Hydrus-1D are powerful quantitative tools to study infiltration and recharge processes, these models require substantial expertise and effort to set up and run, limiting their accessibility by stakeholders to evaluate recharge potentials. This barrier can be overcome by developing nimble, easy-to-run surrogate models.

Surrogate modeling has gained momentum in various engineering fields as a means of reducing computational costs when studying complex systems. In water resources applications, Razavi et al. (2012) provide a broad overview of how surrogate models, built to emulate computationally expensive high-fidelity models, can be employed to simulate and optimize water-related processes more efficiently. Their taxonomy of surrogate modeling underlines the practical steps needed to replace computationally expensive, high-fidelity models with approximations that retain strong predictive capabilities.

Adaptive sampling is a strategy commonly used in surrogate modeling when the high-fidelity model is highly computationally expensive. For example, Borisut and Nuchitprasittichai (2023) illustrate how a carefully chosen sampling strategy can further enhance surrogate-based studies. By adaptively refining a Latin hypercube design, they efficiently identify those regions of input space most critical to model accuracy, thereby minimizing the number of required simulations. This approach proves especially useful for high-dimensional problems, such as multi-parameter process optimization, where random sampling alone would be excessively time consuming.

Of particular importance in recharge potential assessment is determining whether recharge will occur given specific soil and boundary conditions. Lieu et al. (2022) propose an adaptive surrogate framework for identifying “boundary” conditions in structural reliability problems. Although their study addresses structures rather than groundwater systems, the concept of adaptively refinining on a critical limit state, i.e., the point at which a structure transitions from safe to failed, could be applied to identifying the threshold at which a hydrologic system transitions from no recharge to active groundwater recharge. In both cases, the surrogate model guides sampling around the boundary conditions of interest, ensuring that the most relevant regions of parameter space are well approximated. For practitioners aiming to minimize the boundary of conditions causing groundwater recharge, the adaptive approach outlined by Lieu et al. (2022) provides a valuable template for pinpointing and refining critical points of transition in complex, high-dimensional systems.

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