Regional Base-Flow Index in Arid Landscapes Using Machine Learning and Instrumented Records

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Abstract

Base flow, sustained by groundwater discharge, is a vital component of river ecosystems, particularly in drylands, where water resources are limited. This novel study analyzes the instrumented streamflow record in Arizona to assess long-term base-flow index (BFI) trends across gauged catchments. Results indicate that approximately 32% of Arizona’s streamflow originates from groundwater discharge, with significant spatial variability driven by landscape and climatic factors. Base-flow relationships are analyzed with coincident trends in climate variables such as precipitation, evapotranspiration, and temperature. Spatial and climatic trends reveal variability in base-flow contributions, providing insight into groundwater-surface water interactions in arid and semi-arid landscapes. Building on this analysis, we applied machine learning methods to predict BFI in ungauged basins, addressing the challenges of Arizona’s sparse streamgage network. Using the eXtreme Gradient Boosting (XGBoost) algorithm trained and validated on observed hydroclimate and physiographic variables, we estimate long-term BFI from 1991 to 2020. Results indicate spatial heterogeneity in BFI trends, with decreasing baseflow most pronounced in warm-dry and monsoon-dominated catchments. This combined approach integrates observational data with predictive modeling to enhance our understanding of base-flow processes and provide a framework for water resource management in data-limited regions.

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### Key Points

* Approximately 32% of Arizona’s streamflow originates from groundwater discharge.
* XGBoost predicted long-term BFI in ungauged basins, filling dryland data gaps.
* Baseflow trends track precipitation, emphasizing climate’s role in dryland hydrology.

## Introduction

Dryland regions, encompassing arid, semi-arid, hyper-arid, and dry sub-humid systems, cover 40% of the Earth’s land surface. These regions are home to approximately 2 billion people globally and constitute the largest terrestrial biome (IUCN 2019). Despite supporting diverse ecosystems and human populations, dryland regions face mounting hydrologic challenges exacerbated by increasing urbanization, expanding agricultural activities, and climate-induced amplification of precipitation patterns (Taylor et al. 2013). This water scarcity is intensifying due to the compounding effects of climate variability and increased groundwater extraction (Taylor et al. 2013). Groundwater serves as a vital resource in drylands for sustaining ecological functions and supporting human livelihoods (Scanlon et al. 2006; Yao et al. 2018).

Base flow is the sustained portion of streamflow in the absence of runoff that is derived from groundwater discharge (USGS 2018). Base flow is critical to maintaining seasonal low-flow regimes, supporting aquatic ecosystems, and facilitating the transport of nutrients and chemicals. Base-flow contribution to streamflow can be highly variable spatially (Singh et al. 2018; Bosch et al. 2017; Beck et al. 2013), and temporally (Ficklin et al. 2016; Tan et al. 2020). Increasing groundwater extraction, changes in land cover/land use, and changes in precipitation patterns due to climate change affect the timing and volumes of base flow (Tan et al. 2020; Taylor et al. 2013). Effective management of water quantity and quality depends on understanding seasonal and interannual base-flow patterns and long-term changes in base-flow behavior.

The Base-Flow Index (BFI) is the ratio of the long-term mean base-flow volume to the long-term total streamflow volume expressed as a percentage. BFI serves as a normalized measure of groundwater contribution interannually or between basins. BFI is determined by hydrograph separation and is influenced by the climate and physiographic characteristics of a catchment (Neff et al. 2005; Beck et al. 2013; Singh et al. 2018). Between catchments, base flow fluctuates according to changes in the moisture content of the vadose zone, influenced by varying levels of evapotranspiration and aquifer storage dynamics (Bosch et al. 2017). Since BFI calculations rely on instrumented stream records, it remains unknown for ungauged catchments, which encompass most of the earth’s land surface (Fekete et al. 2007). Addressing this information gap is integral to approaching a comprehensive understanding of groundwater dynamics globally. This study addresses this gap by analyzing long-term BFI patterns across Arizona using instrumented streamflow records and applying a machine learning model to predict BFI in ungauged catchments.

Advancements in machine learning provide tools to predict hydrologic indices in ungauged basins, addressing the limitations of sparse streamgage networks. To tackle the challenge of quantifying base-flow indices in ungauged catchments, numerous studies have applied both regression and machine learning methods. Ahiablame et al. (2013) found that using a regression model to estimate annual base flow of ungauged catchments was reasonably easy and accurate. Beck et al. (2013) overcame the nonlinearity of basin characteristics and improved results of multivariate analyses by using artificial neural networks (ANN) to estimate BFI globally. Singh et al. (2018) implemented a random forest algorithm to predict long-term BFI for ungauged catchments across New Zealand. These applications demonstrate the versatility and effectiveness of machine learning in capturing complex ecohydrologic dynamics and improving our understanding of groundwater contributions to streamflow.

Previous studies have examined base-flow regionalization and synthesis across various spatial scales, from global to continental (Beck et al. 2013; Santhi et al. 2008; Ayers et al. 2022; Singh et al. 2018). Such large-scale analyses often utilize generalized datasets and methodologies, resulting in limited applicability to regions with unique hydrogeologic and climatic conditions. Additionally, global and continental-scale studies tend to rely on streamgage networks that disproportionately represent large perennial rivers and regulated watersheds with dense human populations, while underrepresenting arid and semi-arid regions characterized by non-perennial flow regimes and smaller streams (Krabbenhoft et al. 2022). Thus, their effectiveness in accurately capturing groundwater-surface water interactions, particularly in critically water-stressed dryland regions, remains constrained.

To address these limitations, this study focuses on Arizona’s arid and semi-arid basins, where groundwater–surface water interactions remain poorly characterized due to sparse monitoring and regionally distinct hydrologic behavior. We develop a region-specific machine learning model using eXtreme Gradient Boosting (XGBoost) to estimate long-term BFI (1991–2020) across ungauged basins, incorporating basin hydrogeology and hydroclimate predictors. To our knowledge, this is the first map of spatially distributed BFI in Arizona. In parallel, we assess trends in BFI at instrumented sites alongside coincident changes in precipitation, temperature, and reference evapotranspiration. Together, these analyses provide new insight into the spatial patterns and temporal dynamics of baseflow in a water-stressed region increasingly affected by climate change. The study objectives are to (1) quantify long-term spatial and temporal trends in BFI across Arizona and (2) develop a predictive model to estimate BFI in ungauged basins based on geospatial and climate variables.

## Methods

### Study Area

Arizona, located in the southwestern United States, spans approximately 295,253 km² and encompasses a diverse range of landscapes, elevations, and climate regimes. The state includes portions of two major physiographic regions: the Colorado Plateau in the northeast, the Basin and Range province in the south and west, and a transitional zone, the Central Highlands, between them. This heterogeneity results in substantial variation in environmental conditions across the state. The Colorado Plateau is characterized by high-elevation desert and mountain woodlands, averaging 1,936 masl (6,352 ft), with mean temperatures ranging from -6°C (20°F) to 26°C (80°F) and annual precipitation of about 580 mm (23 in). In contrast, the Basin and Range region is lower in elevation, averaging 490 masl (1,600 ft), and features a semi-arid to arid climate, with temperatures ranging from 15°C (60°F) to 43°C (110°F) and an average annual precipitation of 200 mm (8 in) (Arizona State Climate Office 2024). The Central Highlands feature a mix of mountainous terrain and interspersed basins, adding to the state’s topographic and hydroclimatic complexity.

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| Figure 1: Map of Arizona and US Geological Survey (USGS) streamgages used in this study. 8-digit HUC subbasin boundaries and physiographic regions shown. |

Arizona’s hydrology varies seasonally and spatially between its physiographic regions. In summer, localized and intense convective storms stem from the North American Monsoon; in winter, orographic precipitation is delivered by Pacific frontal systems (Eastoe et al. 2019). While monsoonal precipitation can account for up to 50% of annual precipitation, evaporation and dry preceding soil properties leads to most precipitation becoming runoff (Sheppard et al. 2002). As such, 94% of streams in Arizona are ephemeral or intermittent (Levick et al. 2008). Much of the hydrology of Arizona is snow-melt derived, driven by spring melt from the high-elevation Colorado Plateau winter snowpack. Though winter precipitation accounts for only 30% of annual precipitation totals, it provides the majority of water for natural reservoirs (Sheppard et al. 2002).

### Data

Daily observed streamflow data obtained from the United States Geological Survey (USGS) National Water Information System (NWIS) were used in this study. Streamgages were selected depending on criteria to ensure the applicability of each site. Following the findings of O’Donnell et al. (2016), which determined that 8–10 years of calibration data are necessary to account for climate variability in paired watershed studies in the region, a minimum record length of 10 years was required. Additionally, years with more than 30 missing days of streamflow data were excluded from the analysis. Streamgages directly downstream of major regulation (e.g., reservoirs, lakes, diversions) were excluded, based on USGS annual water data reports and site metadata (USGS 2010). While some flow alteration is widespread, the focus was on removing gauges with clear, immediate regulatory impacts. As such, streamgages along the Colorado River were omitted because they represent managed flows governed by the Colorado River Compact. After applying these selection criteria, 205 USGS streamgages with acceptable periods of record were included in the study ([Figure 1](#fig-study-area)). Periods of record ranged from 10 to 112 years, with a median of 28 years.

Our data selection criteria ensure a robust analysis but also highlight notable spatial gaps that our machine learning model can address. Arizona has 184 active USGS streamflow stations (as of 2024) covering an area of 295,253 km². For comparison, Indiana (a humid state in the U.S.) maintains 189 active stations within a significantly smaller area of 94,326 km². This results in a streamgage density of approximately 2.004 gauges per 1,000 km² in Indiana, more than three times greater than Arizona’s density of 0.623 gauges per 1,000 km². Such disparities in gauge coverage are typical for dryland regions globally (Krabbenhoft et al. 2022), underscoring the necessity and relevance of this type of modeling approach in arid and semi-arid environments.

Watersheds across the United States are delineated by the USGS using a hydrologically-defined network. This system delineates the country using hierarchical hydrologic unit codes (HUCs), where each subsequent basin includes the digits of the enclosing basin. Here, 8-digit HUCs (HUC 8s) are used to divide Arizona into 84 sub-basins that are fully or partially in the state ([Figure 1](#fig-study-area)). These HUC 8 sub-basins are analogous to medium-sized river basins and are defined by surface water characteristics.

Annual precipitation and temperature data came from the PRISM climate group at Oregon State University at a resolution of 4 km (<https://prism.oregonstate.edu;> (Daly et al. 2008)). The PRISM dataset provides valuable insights into regional climate in ungauged regions and has been shown to perform well across the southwestern US (Buban et al. 2020). Instead of the water year, PRISM data uses a calendar-year format, which was adopted for consistency in the water balance. Although this may introduce challenges in the annual estimates due to inter-annual snow storage, the use of long-term annual averages reduces potential errors (Reitz et al. 2017).

Annual reference evapotranspiration (ETO) data came from TerraClimate, a 4-km grid climatological data set (Abatzoglou et al. 2018). TerraClimate uses a Penman-Monteith approach to generate a reference evapotranspiration. The ETO values were calculated assuming a reference grass surface across the landscape with unlimited water. In the drylands of the southwestern US, ETO typically exceeds precipitation annually (Zomer et al. 2022).

Basin elevation was derived from a 30-meter resolution Digital Elevation Model (DEM) from the USGS National Elevation Dataset (NED). The DEM of Arizona was used to derive key basin characteristics: basin area, basin slope, and the proportion of each basin oriented toward north or south aspects. Various geospatial variables, such as aspect, were disaggregated then averaged to assess the areal percentage of each sub-variable within individual HUC 8 basins. By calculating these percentages, we derived a more comprehensive understanding of landscape composition across space. Land cover was acquired from USGS-NLCD (National Land Cover Database), hydrologic soil group from SSURGO (Soil Survey Geographic Database), and underlying geology and karst from USGS were all similarly averaged across the basins. Aggregating variables to align with the HUC 8 boundaries allowed for more precise predictions of BFI by integrating spatial variations within each basin.

### Base-flow separation

Directly measuring base flow and base-flow index (BFI) presents unique challenges (Eckhardt 2008). Base flow is a physical hydrologic process representing groundwater contributions to streamflow, while BFI is a dimensionless, statistical metric that estimates the proportion of streamflow derived from base flow. Because BFI must be derived using a base-flow separation technique, its value is inherently method-dependent and sensitive to the separation approach used (Beck et al. 2013). A variety of techniques have been developed to estimate base flow, including tracer studies (Gonzales et al. 2009), graphical interpolation methods (Hydrology 1980; Sloto et al. 1996), and digital filters (Arnold et al. 1995; Eckhardt 2005; Lyne et al. 1979; Nathan et al. 1990). Each of these methods varies in its applicability depending on spatial scale, record length, and study objectives. Although the choice of separation method and parameterization introduces some subjectivity, these filters have been shown to yield reliable estimates when applied consistently within a study domain (Chapman 1999; Eckhardt 2005; Hydrology 1980; Ayers et al. 2022). Numerous studies have compared these separation techniques (e.g., Eckhardt 2005, 2008; Nathan et al. 1990); however, this study does not evaluate the relative performance of different methods.

Base flow was calculated using a single-parameter, recursive digital filter technique from Nathan et al. (1990). This base-flow separation technique is based on a recursive digital filter used in signal analysis that separates high-frequency signals (quickflow) from low-frequency signals (base flow) (Lyne et al. 1979). Eckhardt (2023) noted that recursive digital filters lack a physical basis, but as the method is easy to automate, objective, and repeatable, it is appropriate for a regional-scale study. The Lyne-Hollick filter has been used in multiple studies (Arnold et al. 2000; Santhi et al. 2008; Bloomfield et al. 2009; Singh et al. 2018), and it takes the form of

where is base flow, is the filter parameter, is the total streamflow, and is the time step. A filter parameter of 0.925 was used as in Nathan et al. (1990) and Fuka et al. (2014). The filter was run three times (forward, backward, forward) to attenuate the base-flow signal.

Two BFI metrics were used in this study: (1) annual BFI, calculated for each calendar year using daily streamflow records, and (2) long-term BFI, defined as the average of annual BFI values over the period of record at each site. Annual BFI reflects interannual variability in base-flow contributions, while long-term BFI represents a time-averaged metric of groundwater influence. The machine learning model was trained to predict annual BFI values, which were then aggregated to produce long-term BFI estimates.

### Machine Learning

Machine learning (ML) approaches have demonstrated strong utility in hydrologic prediction tasks, including the estimation of streamflow and base-flow indices (Singh et al. 2018; Schmidt et al. 2020; Rozos et al. 2021). In this study, we used the eXtreme Gradient Boosting (XGBoost) algorithm (Chen et al. 2016) to estimate annual BFI at ungauged locations across Arizona using catchment characteristics as predictors [Table 1](#tbl-predictors). XGBoost is a gradient boosting algorithm that builds an ensemble of decision trees, where each tree iteratively corrects errors from previous trees to improve predictive accuracy (Chen et al. 2016). To our knowledge this is the first time that this advanced, decision-tree algorithm has been used in hydrologic prediction. The model was trained on annual BFI observations in order to estimate annual BFI in ungauged basins. These annual BFI estimates were averaged over time to represent long-term BFI, consistent with the time-integrated nature of our response metric.

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| Table 1: Basin-characteristic variables used in reduced XGBoost model. A list of initial predictor variables used in the full model is provided in the Supplemental Information.   |  | Variable | Source | Geoprocessing | | --- | --- | --- | --- | | Hydroclimate | Temperature | PRISM | Basin Mean | |  | Mean Precip | PRISM | Basin Mean | |  | Reference ET | MODIS | Basin Mean | | Geospatial | Elevation | DEM | Basin Mean | |  | Soil Type A | SSURGO | % Areal Coverage | |  | Soil Type C | SSURGO | % Areal Coverage | |  | Land Cover - Open Water | NLCD | % Areal Coverage | |  | Land Cover - Low Develoment | NLCD | % Areal Coverage | |  | Land Cover - Evergreen Forest | NLCD | % Areal Coverage | |  | Land Cover - Herbaceous | NLCD | % Areal Coverage | |

The training dataset consisted of 7,724 site-year observations, where each observation represents annual BFI for a single year at a given USGS streamgage. These observations are paired with 45 predictor variables derived from basin characteristics and climate data. Predictor selection was based on prior hydrologic studies and data availability across the study area. The predictors included basin-averaged climate metrics (e.g., precipitation, temperature), topographic features (e.g., elevation, slope), and land surface attributes (e.g., land cover classes, soil type, presence of karst).

We tested multiple model configurations, including versions with the full predictor set across the state, separate models for physiographic regions with full predictor set, and reduced subsets across the state, to evaluate the impact of different predictor combinations on model performance and to ensure robustness of the final selected model. Dimensionality reduction was performed to improve interpretability and reduce computational burden. We applied SHAP (SHapley Additive exPlanations) values (Lundberg and Lee 2017) to assess global feature importance and rank predictors. SHAP was chosen for its interpretability and ability to account for feature interactions (Lundberg and Lee 2017). The values quantify both the magnitude and direction of each feature’s contribution to predictions. The ten most important features, based on SHAP value, were retained in a reduced model. The reduced model showed improved predictive accuracy and efficiency over the full model and regional models. Sensitivity analyses tested region-specific models and smaller predictor subsets; however, the state-wide model using SHAP-prioritized features outperformed alternatives. The final model was applied to all HUC8 basins across Arizona using the same predictor layers to estimate long-term BFI values.

The model dataset was evaluated using 10-fold cross-validation, ensuring robust performance estimates and guarding against overfitting [Figure 2](#fig-k-fold) . In each iteration (fold), the model was trained on 90% of the data and validated on the remaining 10%, with folds being rotated until all of the data had been used for validation in separate models. Root mean squared error (RMSE) was used as the primary performance metric. Model performance on unseen data was strong, with an overall R² of 0.764.

To contextualize model accuracy, we compared XGBoost to two baseline methods: a simple linear regression and an inverse distance weighting (IDW) interpolation. XGBoost reduced RMSE by 43% relative to the linear model and 30% relative to IDW, while improving NSE from 0.25 (linear) and 0.45 (IDW) to 0.75, indicating substantially stronger predictive accuracy and spatial generalization.

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| Figure 2: Schematic of $k$-fold cross validation. The dataset is randomly divided into $k$ stratified folds. Each fold serves as the validation set once, while the remaining folds are combined to create a training set for model development. Performance metrics for the test set are calculated and recorded, and this process is repeated for all $k$ folds. |

Hyperparameter tuning was performed through an internal grid search. The search evaluated combinations of parameters including the number of trees, learning rate (), minimum split loss (), tree depth, and minimum child weight. A description of these hyperparametes can be found in Chen et al. (2016). The final model used 700 trees, of 0.05, of 0.075, a maximum depth of 7, and a minimum child weight of 5. All parameters were selected for their reduction in RMSE across validation folds.

### Statistical Analyses

Statistical analyses were conducted on annual BFI values from instrumented streamgages to identify site-specific temporal trends using the Mann–Kendall nonparametric trend test (Kendall 1970; Mann 1945). This test detects monotonic trends in non-normally distributed data and assumes the absence of autocorrelation. This test is widely used in hydrologic trend studies (Ficklin et al. 2016; Ayers et al. 2019; Woodhouse et al. 2022).

To account for potential autocorrelation in annual BFI time series at each instrumented site, we applied the Durbin–Watson test (Durbin and Watson 1950). Four streamgages exhibited significant autocorrelation; these sites were excluded from the trend analysis to avoid inflated variance in the Mann–Kendall statistic and potential bias in trend detection (Hamed and Rao 1998). As all autocorrelated series were removed, pre-whitening using the Hamed–Rao method was unnecessary (Hamed and Rao 1998). Trends with a are considered significant.

## Results

### Observed BFI in Gauged Catchments

The long-term BFI for the 205 gauged reaches across Arizona is illustrated in [Figure 3](#fig-instrumented-bfi) . The long-term mean BFI is 0.32, indicating that ~32% of long-term streamflow in Arizona likely originates from groundwater discharge and other delayed sources. The highest long-term BFI values (>0.9) are found along the Grand Canyon in northwestern Arizona, where highly karstic geology facilitates rapid subsurface flow to surface water and spring outlets (Chambless et al. 2023). High long-term BFI values (>0.8) are also found at the spring-fed headwaters of the Verde River and Fossil Creek, which have similar highly-karstic, snowmelt-driven recharge areas.

The stream reaches of the Little Colorado River Basin (northeastern Arizona) indicate low long-term BFI values (< 0.2). This is likely due to low-yielding perched aquifers underlying the Defiance Plateau in northeastern Arizona, which are hydrologically connected to surface streams, while the high-yield, confined regional aquifer is much deeper (Blanchard 2002).

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| Figure 3: Long-term BFI for the period of record from instrumented stream flow data. |

#### Trends in Annual BFI

Trends in annual BFI over the period of record for each streamgage are illustrated in [Figure 4](#fig-instrumented-trend) and summarized in [Table 2](#tbl-trends). Annual BFI trends were assessed at all instrumented sites using the Mann–Kendall test. As BFI quantifies the proportion of streamflow attributed to base flow, its long-term trends inherently reflect changes in subsurface contributions relative to total flow. A 72.2% coincidence rate between significant base-flow volume and BFI trends supports the interpretation that changes in BFI are largely driven by underlying base-flow dynamics. Statistically significant long-term BFI trends were observed across numerous sites, with spatial variation highlighting regional differences in hydrologic response.

[Figure 4](#fig-instrumented-trend) illustrates the spatial variation in long-term BFI trends across the study area. Statistically significant decreasing trends are observed at 16.1% of sites, while increasing trends are found at 8.8% of sites. No consistent regional patterns are evident.

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| Figure 4: Trends in BFI over full period of record for instrumented sites used in this study. Red downward (blue upward) arrows indicate a decreasing (increasing) trend at a significance level of 5%. White circles represent sites with no statistically significant trends. |

#### Classification Trends

Classifications presented in [Table 2](#tbl-trends) were determined based on precipitation regime, physiographic region, climate, and slope. The dominant precipitation regime (monsoon vs. snowmelt) was identified by analyzing streamflow hydrographs for each station, focusing on peak flow periods during the monsoon season (July–September) and the snowmelt season (March–June). Physiographic region was assigned based on which region the streamgage is located. Climate classifications were defined as warm (above the long-term median temperature of Arizona), cool (below the long-term median temperature), wet (above the long-term median precipitation), and dry (below the long-term median precipitation). Slope was categorized as high (above the median slope) and low (below the median slope).

Statistically significant decreasing trends in long-term BFI were more common than increasing trends across all site classifications ([Table 2](#tbl-trends)). While decreasing trends dominate, both increasing and decreasing trends are observed within each classification. Monsoon-dominated regions exhibit a higher proportion of significant negative trends (24.1%) compared to snowmelt-dominated regions (10.2%), suggesting that monsoon-dominated systems are more consistently correlated with declining long-term BFI. Among climate classifications, warm-dry climates have the highest proportion of negative trends (20.0%), followed by warm-wet climates (19.4%), indicating that regions with higher temperatures are more prone to BFI declines. Low-slope regions show a greater prevalence of negative trends (20.4%) compared to high-slope regions (11.8%). This suggests that flatter areas may be more susceptible to base-flow reductions, potentially due to differences in hydrologic connectivity and recharge dynamics. Negative trends in low-slope regions may also be a result of reductions in water table height, assumed to follow topography, leading to a change in flow direction.

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| Table 2: Comparison of trends for BFI for all sites split by various classifications. Only sites with a significant () trend are included here as established by a Mann-Kendall test for monotonic trends across the full period of record. n is the number of sites, n\_pos (n\_neg) is the number of sites with positive (negative) trends, perc\_pos (perc\_neg) is the percentage of n with a positive (negative) trend.   | **Classification Group** | **n** | **n\_pos** | **n\_neg** | **perc\_pos** | **perc\_neg** | | --- | --- | --- | --- | --- | --- | | Precipitation - Monsoon Dominated | 87 | 8 | 21 | 0.092 | 0.241 | | Precipitation - Snowmelt Dominated | 118 | 9 | 12 | 0.076 | 0.102 | | Physiographic Region - Basin and Range | 156 | 14 | 26 | 0.090 | 0.167 | | Physiographic Region - Colorado Plateau | 49 | 3 | 7 | 0.061 | 0.143 | | Climate - Warm-Wet | 31 | 2 | 6 | 0.065 | 0.194 | | Climate - Warm-Dry | 55 | 6 | 11 | 0.109 | 0.200 | | Climate - Cool-Wet | 74 | 4 | 9 | 0.054 | 0.122 | | Climate - Cool-Dry | 45 | 5 | 7 | 0.111 | 0.156 | | Slope - High | 102 | 10 | 12 | 0.098 | 0.118 | | Slope - Low | 103 | 7 | 21 | 0.068 | 0.204 | |

#### Coincident Climate Trends

Coincident trends are defined as those in which long-term BFI trends match in direction with climate variable trends over the same period. Results are summarized in [Table 3](#tbl-coincident-trends). This analysis includes both significant and non-significant trends, which is appropriate where the influence of complex, interconnected processes may not always manifest as statistically significant patterns over limited observational periods (Ficklin et al. 2016). Long-term BFI coincided most with precipitation (53.17%), followed by ETO and then temperature. Temperature trends most often show an inverse relationship—i.e., warming associated with declining BFI and base flow.

Given the variations in the period of record across the instrumented network (see Figure S2), we analyzed trends of long-term BFI in relation to coincident trends in climate variables. Trends are classified as coincident when the direction of the climate variable trend (positive or negative) aligns with the trend observed in BFI ([Table 3](#tbl-coincident-trends)).

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| Table 3: Coincident trends of climate variables (ETO, precipitation, temperature) with BFI trends.   |  | **Climate Variable** | **Coincidence Percentage (%)** | | --- | --- | --- | | BFI | ETO | 44.88 | |  | Precipitation | 53.17 | |  | Temperature | 47.32 | |

### BFI of Ungauged Catchments

#### Model Validation

Predicted values of annual BFI are plotted against observed values for the entire period of record of the instrumented dataset in [Figure 5](#fig-actual_predicted) . The agreement between “out-of-bag” predictions (blind cross-validation, treating each site as ungauged) and observed values indicate strong model performance across the full dataset (R2 = 0.764). The overall RMSE is 0.129 and the overall percent bias (pbias) is -5.6%.

Model performance metrics across various classifications are summarized in [Table 4](#tbl-performance). These metrics show consistent model performance across spatial and climatic classifications. However, the negative pbias values across all classifications indicate a systematic underprediction of annual BFI. Categories with relatively lower R2 and Nash-Sutcliffe Efficiency (NSE) values also exhibit higher biases, reflecting weaker model performance in those contexts.

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| Figure 5: Linear relationship between observed BFI and predicted BFI. The solid line is the 1:1 line, the dashed, green line is regressed to the data. |

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| Table 4: Performance of model predictions for annual BFI for all sites split by various classifications. n is number of observations, R2 is the coefficient of determination of a linear regression, MSE is mean-squared-error, RMSE is root-mean-squared-error, MAE is mean-absolute-error, NSE is Nash-Sutcliffe efficiency, and pbias is percent bias.   | **Classification Group** | **n** | **R2** | **MSE** | **RMSE** | **MAE** | **NSE** | **pbias** | | --- | --- | --- | --- | --- | --- | --- | --- | | Full Dataset | 7724 | 0.764 | 0.015 | 0.122 | 0.081 | 0.752 | -5.6 | | linear model | 7724 | 0.248 | 0.046 | 0.214 | 0.173 | 0.247 | ~ 0 | | Inverse Distance Weighted (LOO CV) | 7724 | 0.449 | 0.029 | 0.170 | 0.131 | 0.448 | 1.86 | | Climate - Monsoon Dominated | 3039 | 0.633 | 0.016 | 0.126 | 0.074 | 0.619 | -13.7 | | Climate - Snowmelt Dominated | 4685 | 0.733 | 0.015 | 0.121 | 0.087 | 0.725 | -3.5 | | PhysRegion - Basin&Range | 6147 | 0.733 | 0.016 | 0.127 | 0.084 | 0.724 | -6.3 | | PhysRegion - CO Plateau | 1577 | 0.846 | 0.011 | 0.104 | 0.073 | 0.843 | -3.8 | | Climate - Warm-Wet | 1506 | 0.693 | 0.014 | 0.117 | 0.077 | 0.685 | -8.2 | | Climate - Warm-Dry | 2351 | 0.693 | 0.022 | 0.147 | 0.092 | 0.675 | -11.9 | | Climate - Cool-Wet | 2350 | 0.738 | 0.011 | 0.106 | 0.078 | 0.736 | -1.7 | | Climate - Cool-Dry | 1517 | 0.831 | 0.012 | 0.111 | 0.078 | 0.827 | -4.3 | | Slope - High | 3795 | 0.776 | 0.012 | 0.111 | 0.079 | 0.771 | -3.3 | | Slope - Low | 3929 | 0.724 | 0.018 | 0.133 | 0.085 | 0.713 | -9.1 | |

#### Predictor Importance

The predictors used to estimate annual BFI at ungauged sites were evaluated for their importance in the final XGBoost model, as illustrated in [Figure 6](#fig-shap_values). The most influential feature for predicting annual BFI is basin elevation. While elevation itself does not directly affect base-flow characteristics, it has consistently been identified as a key predictor in previous BFI studies (Singh et al. 2018; Beck et al. 2013). The importance of elevation aligns with findings from Beck et al. (2013), highlighting its role as a proxy for climate variables such as temperature, precipitation, and snowpack duration. Seasonal snowpack duration, in particular, has been shown to strongly correlate with springflow and groundwater recharge in this region (Donovan et al. 2022).

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| Figure 6: SHAP value plot of features used in final model. The number to the right of the feature name is the mean absolute SHAP value. Land cover features are indicated by the percentage of cover by each land cover type and soil types are defined by hydrologic soil group. |

Land cover and land use predictors also play a significant role in annual BFI estimation. Analysis of SHAP values indicates that a higher percentage of evergreen forest positively influences BFI predictions, while higher proportions of shrubland and developed land exert a negative influence. Similarly, hydrologic soil types show distinct trends in their impact on BFI. Soil Type C, characterized by moderately high runoff potential (20-40% clay), tends to negatively influence BFI. In contrast, Soil Type A, which has low runoff potential and facilitates rapid water infiltration, exhibits a mixed influence (USDA 2009).

#### Predicted BFI in Ungauged Basins

Predicted long-term BFI (1991–2020) across Arizona’s HUC-8 basins is shown in [Figure 7](#fig-bfi-huc). Higher values were observed along the Grand Canyon corridor and parts of the Mogollon Rim, while lower values were found across the Defiance Plateau and in southern Arizona. Spatial variation generally aligns with physiographic regions and precipitation gradients, with upstream reaches of perennial rivers typically exhibiting higher BFI.

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| Figure 7: Predicted long-term BFI values for 8-digit HUC (1991-2020). Bolded HUCs indicate those without a streamgage. |

## Discussion

The existing streamgage networks in Arizona are limited for base-flow analyses by their design and monitoring objectives. While the number of streamgages has increased to meet regulatory imperatives, such as those driven by the Clean Water Act, many gauges prioritize peak flow monitoring rather than low-flow conditions critical for base-flow studies (Maricopa County 2020). Newer non-USGS gauges, such as those installed by flood control districts (e.g., the ALERT system), are generally tailored for flood detection rather than monitoring sustained base flow. Recent USGS installations focus on addressing in-stream flow rights and future monitoring improvements, though low-flow capabilities remain limited.

Given the limited coverage provided by existing gauges, a common issue in arid and semi-arid regions globally (Krabbenhoft et al. 2022), we utilized a machine learning approach to estimate annual BFI in ungauged catchments. The regional model exhibited strong predictive capability (overall R²=0.764), though systematic underprediction (negative pbias) was noted, particularly in monsoon-dominated and warm-dry climates. These biases highlight opportunities to improve model performance through incorporating additional predictors or refining regional hydrologic representations. Although creating separate regional models (by physiographic region) was explored to enhance predictive accuracy, the state-wide model consistently outperformed these regionalized approaches, emphasizing the advantage of a comprehensive, state-wide dataset.

The spatial patterns in BFI reflect underlying differences in hydrogeologic and climatic drivers. In high-BFI regions such as the Mogollon Rim and Grand Canyon, fractured bedrock, karst systems, and deep regional aquifers provide substantial groundwater discharge to surface waters. These areas benefit from high orographic precipitation and forested landscapes that promote infiltration and recharge. In contrast, low-BFI regions such as the Defiance Plateau and southern Arizona feature shallow or disconnected groundwater systems, low precipitation, and high evaporative demand, all of which limit baseflow contributions. Land cover and soil properties further modulate these processes; areas with high-infiltration soils and perennial vegetation are more conducive to sustained baseflow, while impervious surfaces and fine-grained soils suppress it. The downstream decline in BFI [Figure 3](#fig-instrumented-bfi) is consistent with the transition from headwater recharge zones to more arid, losing stream reaches, highlighting the importance of hydrogeologic setting in shaping baseflow dynamics (Winter 2007).

Analysis of trends at instrumented sites revealed a predominance of declining long-term BFI values, particularly within monsoon-dominated precipitation regimes, warm-dry climates, and low-slope basins. These negative trends likely reflect intensified climate stress, highlighting areas most vulnerable to groundwater depletion and surface-water scarcity. Precipitation was identified as the primary driver influencing base-flow variability, with temperature and evapotranspiration trends adding complexity. The weaker correlation between temperature and BFI trends suggests that temperature impacts are moderated by other environmental factors, underscoring the need for integrated climate and land-management strategies to protect groundwater-dependent ecosystems.

Elevation emerged as the most significant predictor, reinforcing its established role as a proxy for climate conditions influencing groundwater recharge. This aligns with findings from previous studies conducted in diverse landscapes, including New Zealand (Singh et al. 2018), across CONUS (Santhi et al. 2008), and globally (Beck et al. 2013). The mixed influence observed for Soil Type A indicates complexity in infiltration dynamics, suggesting that future research could benefit from explicitly incorporating temporal variables such as snowpack duration, soil moisture, and detailed land-cover characteristics.

The reduced predictor set was selected to maximize interpretability and minimize overfitting. However, incorporating additional variables could improve model performance, especially in capturing regionally complex baseflow dynamics. Subsurface hydrologic characteristics, such as aquifer properties, groundwater depth, and spring density, are known to influence baseflow but were excluded due to limited availability across the study domain. Temporal predictors, including snowpack duration, antecedent soil moisture, and wetness indices, could improve annual BFI predictions by capturing lagged hydrologic responses to climate variability. Additionally, incorporating human influences (for example, groundwater withdrawals, land-use change, or reservoir operations) would be important in regions with modified hydrologic regimes. Future efforts may benefit from integrating these datasets where available, although such improvements would require region-specific data processing and validation strategies.

Several previous studies have examined regional and continental patterns of BFI, offering useful context for our findings despite limited geographic overlap. Beck et al. (2013) developed a global map of BFI using an artificial neural network trained on 1,862 U.S. streamgages from the MOPEX dataset (Schaake, Cong, and Duan 2006). Only ten of these gauges overlap with our Arizona study area, limiting direct comparison. Nonetheless, the spatial distribution of BFI in Arizona from Beck et al. (2013) shows general agreement with our regional patterns. The higher BFI values reported by Beck et al. (2013) may reflect the influence of their global-scale ANN model and associated generalizations. Similarly, Ayers et al. (2022) examined base-flow dynamics using GAGES-II sites across CONUS, but their study included few gauges within Arizona. While exact locations are not specified, their published figures suggests regional agreement with our estimated BFI distributions. Santhi et al. (2008) employed interpolation methods for regional base-flow estimation across CONUS; however, the lack of gauge-level detail limits direct comparison.

In terms of long-term trends, our results align directionally with Ayers et al. (2022) , who found consistent monthly declines in base flow from 1989–2019 across the U.S. Southwest. Although our analysis focused on long-term trends in annual BFI, we observed a similar imbalance: 16% of sites showed significant decreasing trends compared to 8% with increasing trends. While we do not directly replicate their monthly analysis, the directional agreement supports the broader conclusion that groundwater contributions to streamflow are declining in many parts of the region.

The combined use of long-term baseflow trend analysis and XGBoost modeling offers a transferable framework for understanding groundwater–surface water interactions in data-scarce regions globally. This approach is particularly relevant in dryland and seasonally variable climates, where direct baseflow observations are limited and hydrologic responses are strongly shaped by physiography and land cover. Critically, arid regions around the world remain under-instrumented, with sparse monitoring networks and limited long-term streamflow records, despite facing acute water scarcity and growing pressure on groundwater systems (Taylor et al. 2013). The success of such models depends on the availability and quality of climate, topographic, and soil datasets, as well as the representativeness of streamflow records used in training. Regions with differing hydrogeologic settings, such as glacial terrains, humid catchments with deep weathered profiles, or regions with inter-annual snowpack storage, may require alternative predictor variables or model structures. For instance, in humid regions with dense vegetation and shallow groundwater tables, evapotranspiration dynamics may play a more dominant role in baseflow variability, requiring region-specific calibration. Despite these caveats, the generalizable structure of this modeling framework, along with the interpretability offered by SHAP-based feature selection, makes it well-suited for adaptation to other geographic contexts, especially where water resources are vulnerable to climatic and land-use change

## Conclusions

The long-term average BFI across Arizona is approximately 0.32, highlighting that groundwater discharge significantly contributes to surface water flows but exhibits substantial spatial variability. Our machine learning model (XGBoost) effectively predicts annual BFI in ungauged catchments (R² = 0.764), primarily driven by basin elevation, land cover, and hydrologic soil characteristics. Regions such as the Grand Canyon and Mogollon Rim exhibit the highest long-term BFI values, signifying robust groundwater-surface water interactions, whereas areas such as the Defiance Plateau and southern Arizona show consistently lower BFI values, reflecting limited groundwater contributions.

Analysis of temporal trends indicates a prevailing pattern of declining long-term BFI across the region, particularly in monsoon-dominated, warm-dry, and low-slope areas. Precipitation emerged as the strongest driver of base-flow variability, while temperature and evapotranspiration added additional layers of complexity. The observed trends underscore the sensitivity of Arizona’s hydrological systems to climatic variability and suggest increasing vulnerability under projected climate change scenarios and other stresses to aquifers, such as increased groundwater pumping.

This research highlights critical limitations in Arizona’s current streamgage network for monitoring base-flow processes, suggesting a need for targeted investments in instrumentation capable of capturing low-flow dynamics. Additionally, the demonstrated success of our modeling framework accentuates its broader applicability to similarly data-scarce dryland regions globally, providing a valuable tool for water resource management and climate adaptation strategies. By improving our understanding of groundwater-surface water interactions under changing climatic conditions, this study contributes substantially to addressing hydrological uncertainties in arid and semi-arid environments.

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