Aquatic Ecosystems and Environmental Frontiers, Volume 4, Issue 3, September 2026 *ISSN: 3049-186X*
DOI: https://doi.org/10.70102/AEEF/V4I3/AF260301

Hydrological Modeling and Climate Variability Analysis for Sustainable Freshwater Resource Management

[1*] Dr. Srishti Singh Chauhan, Assistant Professor, Kalinga University, Naya Raipur, Chhattisgarh, India. E-mail: ku.srishtisinghchauhan@kalingauniversity.ac.in, Orcid: https://orcid.org/0009-0001-3116-2016

[2] Dr. Abhijeeta Nandha, Assistant Professor, Kalinga University, Naya Raipur, Chhattisgarh, India. E-mail: ku.abhijeetanandha@kalingauniversity.ac.in, Orcid: https://orcid.org/0009-0009-9958-0175

Abstract: Freshwater resources support drinking water provision, irrigation, riverine ecosystems, and livelihoods, but are becoming increasingly influenced by irregular rainfall and increasing air temperatures. The current study was an assessment of the impact of climate variability on the hydrological response and availability of freshwater in the upper Cauvery River basin in Southern India for the period 1991–2020. These were combined in a semi-distributed hydrological model that was calibrated using daily gridded rainfall and observed streamflow data from 1995 to 2008 and validated using the observed streamflow data from 2009 to 2020. The climate variability characterization was conducted using annual anomalies, seasonal distribution, and long-term trends, and the freshwater availability characterization was done using flow duration characteristics and seasonal water yield. Monthly streamflow was well reproduced by the model, with efficiency values of 0.86 in calibration and 0.78 in validation. There was a slight rise in the mean annual temperature of approximately 0.27 °C per decade, and a slight decrease in the mean annual rainfall (8.1%) over the period 1991-2005 to 2006-2020. The mean annual runoff went down 20.7% over the same period, suggesting that streamflow reacted two and a half times more to rainfall. The mean annual water yield decreased from 9.40 to 7.47 billion m^3, while the median monthly flow decreased approximately by one-third. The southwest monsoon produced almost three-fourths of the annual yield, while dry-season flows were very low and becoming more marginal. The results suggest that new hydrological baselines, seasonal storage management, and protected minimum flows and demand management in deficit years should be incorporated into water-allocation planning.

Keywords: Hydrological Modeling; Climate Variability; Streamflow; Freshwater Availability; Water-Resource Management; River Basin.

(Submitted: May 11, 2026; Revised: June 22, 2026; Accepted: August 03, 2026; Published: September 30, 2026)

I. Introduction

Fresh water is a limited resource that is essential for human life, food production, industrial use, and river, lake, and wetland ecology. Whilst water dominates the surface of the globe, only a small portion is available as a renewable resource from rivers, reservoirs and shallow aquifers. The availability of this accessible fraction is mainly observed during a few months of the year in monsoon-dominated regions, and hence, the supply is reliable only when rains are received during those months. Changes in flow have impacts on both people and aquatic resources such as fish, invertebrates, and riparian vegetation in such areas.

The availability of freshwater is strongly affected by climate variability and the time of availability. The variability of rainfall from year to year, increases in the duration of dry or wet years, and the occurrence of a trend towards gradual warming all contribute to the shift in rainfall–evaporation–soil moisture–groundwater recharge–river discharge balance. A higher percentage of rainfall can return to the atmosphere as a result of higher temperatures and the increased moisture needs of the atmosphere. A small change in precipitation, therefore, combined with an increase in temperature, can result in a much greater decrease in flow of the river than the drop in precipitation alone would imply.

Hydrological modeling offers a useful approach to comprehending these interactions. A calibrated watershed model is a representation of the flow of rainfall over the terrain, through the soil, recharging the groundwater, and coming out as streamflow. Once its performance is verified against the observed records, the model can be applied to the deconstruction of climatic signal from other drivers, to the filling of

observation gaps and to the estimation of water availability in the future, under scenarios which have not been experienced. Models thus serve as a link between climate information and operational decisions regarding water allocation, water storage and protection of the ecosystem.

The changing of rainfall and temperature patterns poses various practical issues to water managers. However, rainfall that is shorter and more intense causes higher flood peak flows and less recharge to groundwater or soils. Lack of or slow monsoon onset reduces the usable filling season of reservoirs. An increase in temperature effectively shortens the dry season, reduces base flow, and increases the competition for the use of water by irrigation, urban water supplies, hydropower, and environmental requirements. These pressures have been manifested in river allocation disputes, particularly in years of deficit when the amount of water released by the upstream water holder is insufficient to satisfy the downstream water holder's demand.

Although there has been a lot of research done on climate change and water resources, there are still many gaps. The seasonal storage and release pattern of the supply that controls regulated monsoon basins is not represented in many assessments, which are global or continental scale. Studies on a basin scale often investigate either climate change or model skill only, and do not connect these two with measurable measures of fresh water availability like flow duration and seasonal water yield. Moreover, the newly observed sensitivity of runoff to decreases in precipitation, under a warming climate, has been little studied in tropical basins where water allocation is already a source of contention.

The study aimed to incorporate climate variability analysis with hydrological modeling to evaluate the availability of freshwater in a monsoon-fed river basin and to provide information for sustainable management.

Key Contributions

1. Completes Climate Variability Analysis and Hydrological Modelling to evaluate Freshwater availability.
2. Measures long-term changes in rainfall, temperature, runoff, and water yield in the upper Cauvery River basin.
3. Uses flow-duration and seasonal-yield indicators to identify, high-water and low-water periods on a seasonal and interannual time scale.
4. Offers practical strategies and methods for managing water during reservoir operation, aquifer recharge, ecological flow protection, and drought-water allocation.

The background, research problem, and research contribution of the present study are introduced in Section 1. Section 2 summarizes former research works related to climate variability, hydrological variations, models, and sustainable management of fresh water. Section 3 provides details of the study area, datasets, hydrological modeling procedure, climate variability assessment, calibration, validation, and performance evaluation. The results for rainfall, temperature, streamflow, model performance, runoff, seasonal water yield, and freshwater availability are presented in Section 4. The major findings, the implications for sustainable water-resource planning and management, and the study's limitations are discussed in Section 5, and much of the study concludes with the key findings and recommendations, along with suggestions for future research, in Section 6.

II. Literature Review

Climate Variability and Freshwater Resources

Terrestrial water storage during the last 20 years has been observed from satellites to have intensified with the rise in global mean temperature during extreme dry and wet events (Rodell & Li, 2023). Thousands of gauged rivers have been analyzed, and the observed trends in the mean and extreme river flow have been

attributed to anthropogenic climate change, including a drying trend in several regions of the mid-latitude and subtropical oceans (Gudmundsson et al., 2021). Further, large ensemble climate experiments indicate that many future average climates will be similar to those considered as extreme droughts or extreme wetness (Stevenson et al., 2022). These findings suggest that the historic freshwater supply range is not useful for planning.

Hydrological Changes Under Changing Climatic Conditions

Near-future streamflow declines are larger than Earth system models suggest, primarily due to greater streamflow sensitivity to changes in evaporation than suggested from observation-based estimates (which are derived from more than nine thousand catchments) (Zhang et al., 2023). The failure of the northeast monsoon in southern India for three consecutive years (2016–2018) led to an unprecedented situation of drought in the region, reducing the surface and groundwater storage and leading to increased water scarcity in urban areas (Mishra et al., 2021). Another study on soil-moisture simulations for South Asia indicates that the most severe droughts on record may be more than a factor of 1.5 times more likely to occur in the future (Aadhar & Mishra, 2021). Such studies confirm the importance of considering basin-scale streamflow sensitivity.

Applications of Hydrological Models in Water Management

The hydrological intensification (HYIND), defined by increases in precipitation surpluses and decreases in precipitation deficits, will increase the complexity of reservoir operation and water supply planning in large river basins, as shown by climate-informed modeling (Ficklin et al., 2022). The exposure to river flooding has been shown to grow with warming in global flood modeling based on the latest generation of climate projections, which still has a large spread of uncertainty (Hirabayashi et al., 2021). Nonstationarity necessitates models and statistical techniques for detection and attribution that can incorporate alterations in climate, land cover, and water use (Slater et al., 2020). This use demonstrates the relevance of using models in water management as decision support tools.

Rainfall, Runoff, Streamflow and Water Availability Studies

The availability of data, understanding of processes, model structure, and human-water interactions are common issues that can be tackled for both flood and drought prediction, indicating that both extremes should be addressed within one framework (Brunner et al., 2021). While data-driven methods have opened up new opportunities for streamflow simulation, process-based hydrological knowledge is still vital for understanding model behaviour and applying results to new situations (Nearing et al., 2021). New machine-learning-based forecasting systems have been successful in predicting extreme river flows in ungauged watersheds in numerous countries, and have helped to enhance early warning in data-limited areas (Nearing et al., 2024). Another factor that has become relevant for water-resource management is the increased number of rapid shifts between wet and dry conditions, termed 'hydrological whiplash' (Hammond et al., 2025).

Sustainable Freshwater-Resource Management Approaches

Rapid groundwater declines have been documented in many areas around the globe and groundwater managed recharge can reverse declines in some areas. The rapid onset of multi-year drought, as experienced in western North America, has shown how quickly reservoir storage and river flows can decline under low levels of rainfall and high temperatures. Increasingly, sustainable management strategies include a mix of supply side (storage and recharge) and demand side (conjunctive groundwater and surface water use, environmental flows protection) (Ficklin et al., 2022).

Limitations of Previous Studies

Most previous studies have used coarse resolution global models that lacked good representation of regulated tropical basins and were unable to resolve local reservoir operations (Gudmundsson et al., 2021; Zhang et al., 2023). However, regional drought studies have tended to focus on soil moisture or

meteorological measures, instead of streamflow and usable water yield (Mishra et al., 2021; Aadhar & Mishra, 2021). There have also been methodological reviews that have pointed out the potential for bias in the analysis of hydrological change due to short records and spurious trends and incomplete representation of nonstationary drivers (Slater et al., 2020; Brunner et al., 2021). Moreover, there had been very few studies that have correlated the performance of the model with climate variability and flow-based availability indicators in a coherent way.

Research gap

The existing evidence shows that warming and rainfall variability are impacting streamflow and increasing hydrological extremes, there is limited evidence quantifying the basin-scale impacts on seasonal freshwater availability in monsoon-dominated regulated streams. The present study fills this gap by linking three decades of climate analysis with a calibrated and validated hydrological model, and by presenting the results as flow duration, as well as in the form of seasonal yield and climate–runoff relationships useful for water planning.

III. Methodology

Research Design

A quantitative research design using a model approach was used. A semi-distributed hydrological model was developed from observed climate and streamflow data and spatial catchment data. This 30-year record (1991-2020) was divided into a warm-up period (1991-2005), a calibration period (2006-2015) and a validation period (2016-2020). This record was also split into two 15-year sub-periods (1991-2005 and 2006-2020) to make a comparison of climatic and hydrological conditions. The entire process flow is illustrated in figure 1.

Description of the Study Area

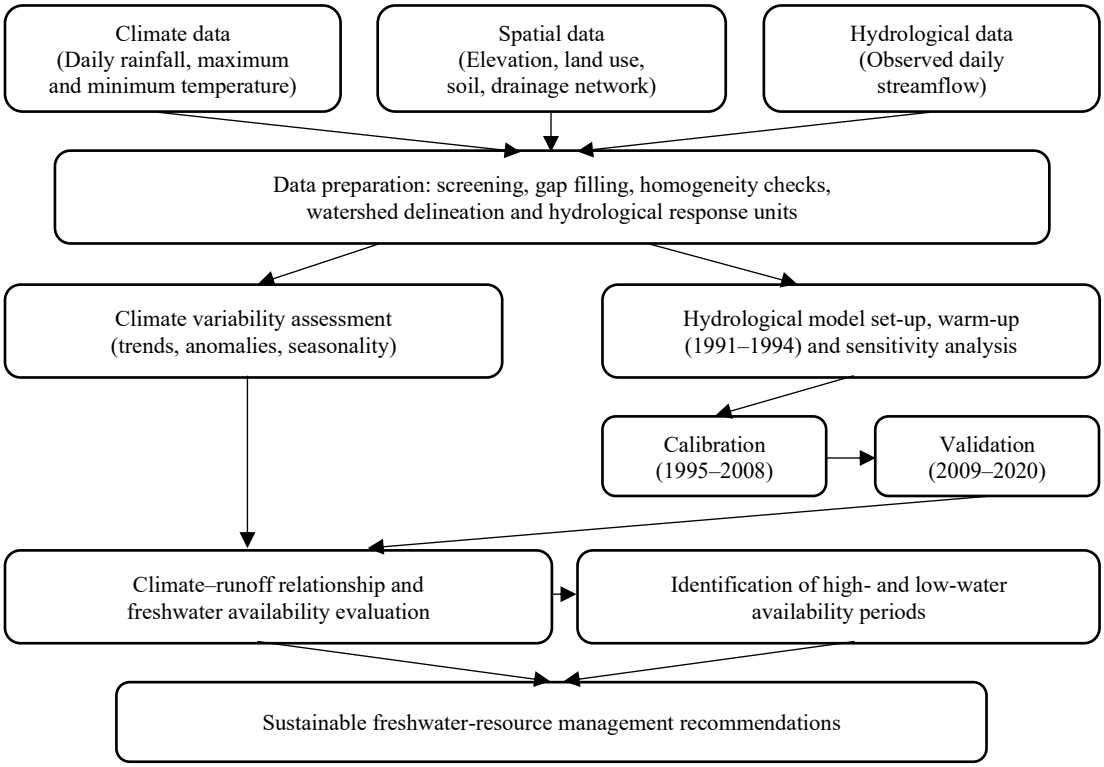


Figure 1: Hydrological Modeling Framework

The study was conducted in the upper Cauvery river basin upstream of the Biligundlu river gauging station which is situated near to the inter-state boundary in the southern part of India with an area of about 36000km2. The basin is the source of water, originating from the Western Ghats and flowing east to the Mysore plateau, where the elevations are more than 1,700 m. The climate is tropical monsoonal, with the south-west monsoonal winds (June to September) bringing the majority of the rains in the western headwaters, and the North-East monsoonal winds (October to December) being significant in the eastern parts. Land use is made up of forests and plantations in the hills and irrigated and rain-fed agriculture on the plateau. Water flow is controlled by several large reservoirs and the river provides drinking-water supply, irrigation, hydropower and locally significant freshwater fish habitat.

Data Collection and Data Sources

The data sources used in the analysis were all publicly available national and international data. Climatological, hydrological, and spatial data pertaining to the upper catchment area of the Cauvery River Basin were utilized for the study. Climatic data, including rainfall and temperature readings from 1991 to 2020, were acquired from the India Meteorological Department, and hydrological data such as streamflows were sourced from the Central Water Commission. The remaining spatial data came from the SRTM, NRSC, and Harmonized World Soil Database. Table 1 summarizes the data types, sources and resolutions.

Table 1: Datasets used in the Study

Data type	Source	Resolution / period
Daily rainfall	India Meteorological Department gridded dataset	0.25° grid; 1991–2020
Daily maximum and minimum temperature	India Meteorological Department gridded dataset	1.0° grid; 1991–2020
Terrain elevation	Shuttle Radar Topography Mission digital elevation data	30 m
Land use and land cover	National Remote Sensing Centre thematic maps	1:250,000
Soil properties	Harmonized World Soil Database	1 km
Observed streamflow	Central Water Commission (India-WRIS portal)	Daily; 1991–2020
Reservoir releases	State water resources departments	Monthly; 1991–2020

Rainfall and Temperature Data Preparation

Rainfall and temperature gridded values were extracted for all the grid cells that were intersected by the basin and were area weighted to the model sub-basins. Less than 1% of the record was missing, the missing values were filled with values from adjacent cells in the record. Before using the series in the model and variability analysis, the following standard homogeneity tests were performed and visual inspection for abrupt shifts and inconsistencies was conducted. Since the spatial resolution of the gridded rainfall data (0.25°) is different from the spatial resolution of the temperature data (1.0°), the temperature data was resampled and then integrated using area-weighted averaging over the sub-basins of the models.

Hydrological and Streamflow Data

The daily discharge data for the Biligundlu station were summarized over the month to calculate the monthly mean. No artificial values were added to missing days, but these days were not used in the comparison process. Monthly releases from the two large upstream reservoirs were added on in order to simulate the effect of regulation on the downstream flow. The monthly figures are aggregated and hence, sub-monthly or daily operation rules which had significant impact on peak flood attenuation and short-term low flow buffering in the upper Cauvery basin could not be captured.

Hydrological Modeling Procedure

A semi-distributed and physically based watershed model was used to simulate the land phase of the hydrological cycle, the Soil and Water Assessment Tool (SWAT). The basin was partitioned into 41 sub-basins from the drainage network and each sub-basin was subdivided into hydrological response units

(HRUs) which are combinations of land use, soil type, and slope. The model simulated surface runoff, infiltration, evaporation from soil and vegetation, lateral flow, groundwater recharge, groundwater baseflow at daily time steps and routed the water through the channel network and reservoirs to the basin outlet.

Climate variability Assessment

Annual and seasonal Rainfall and Mean temperature were calculated for each year. Annual rainfall anomalies were defined as deviations from the 30-year average and years with precipitation more than 200 mm above or below were termed wet or dry years, respectively. The trends were detected with a non-parametric trend test and the size of the trend was calculated by a robust slope method. Mean conditions also were calculated as the difference between the two fifteen-year sub-periods to describe shifts in mean conditions.

Model Calibration and Validation

The years 1991–1994 were used as a warm-up period to establish realistic initial soil-moisture and groundwater conditions. A sensitivity analysis revealed the most important parameters for streamflow, which included those controlling surface-runoff generation, soil water capacity, groundwater delay and base-flow recession, and evaporation compensation. These parameters were tuned in physically relevant limits with an automatic calibration process for 1995 to 2008 and the calibrated model was then not adjusted and validated for the period of 2009 to 2020.

Evaluation of Freshwater Availability

The availability of fresh water was assessed using three indicators. The flow duration curves represented the percentage of the time that the specified flows were exceeded, and high flow, median flow and low flow reference values were selected based on the 10th, 50th, and 90th % exceedance points. The seasonal water yield was defined as the volume of streamflow that passed the outlet for each season. The efficiency of the conversion of rainfall into river flows was expressed by comparing the average depth of runoff to the average depth of rainfall.

Data Analysis and Performance Assessment

Three common criteria were used to evaluate model performance: Nash-Sutcliffe efficiency (deterioration of the variability of the simulated flows), coefficient of determination (deterioration of the timing of the simulated flows), and percentage bias (systematic over or under estimation of the volume simulated flows). The efficiency was judged satisfactory where it was > 0.50, and the percentage bias was within ±15%. Correlation analysis was performed to investigate relationships between annual rainfall, temperature and runoff and the relative sensitivity of runoff to rainfall over the two sub-periods was determined by comparing the proportionate changes between the two variables.

IV. Results

Characteristics of Rainfall and Temperature Variability

Figure 2 indicated a well-understood seasonal rainfall pattern in the basin. About 63% of the annual rainfall received during the southwest monsoon months and 25% during the northeast monsoon months while less than 2% was received during January to March. Maximum temperature was the highest in April prior to onset of the monsoon; minimum temperature was around 16 °C to 22 °C for the entire year.

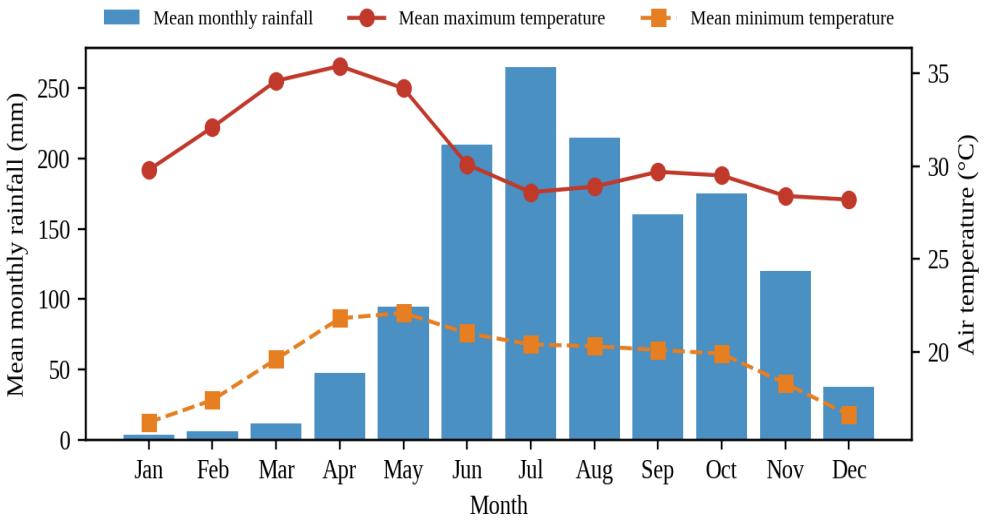


Figure 2: Monthly Rainfall and Temperature Patterns

Seasonal and Annual Hydrological Patterns

Stream flow was well synchronized with the seasonal rainfall regime, with low flow from January to May, followed by a sharp increase to peak flow in July and August. Northeast monsoon season saw a gradual fall in flows. The annual runoff depth averaged 234 mm and the runoff coefficient was approximately 0.19, meaning that about 1/5 of the basin's rainfall was lost to evaporation, stored in soil and aquifers, or diverted for use.

Hydrological Model Performance

The calibrated model was able to simulate the observed monthly streamflow with a good degree of accuracy in table 2. The Nash-Sutcliffe efficiency and the coefficient of determination were still good in validation period (NSE = 0.78 and R2 = 0.86, respectively), but the bias was high at -12.4%, which indicated a moderate systematic overestimation of flow volumes in recent years. This difference over the drier decade from 2009 to 2020 may be related to the fact that some local abstractions were not recorded, or that the local agricultural withdrawals have changed, or that the groundwater pumping dynamics were not represented but increased as this surface water became scarce. The efficiency for calibration and validation was 0.86 and 0.78, respectively, which were higher than the satisfactory value. Coefficients of determination were greater than 0.85 for both periods. Percentage bias was negligible during calibration and within acceptable limits during validation, but slightly negative, suggesting a slight overestimation of flow volume in more recent years.

Table 2: Performance of the Hydrological Model for Monthly Streamflow

Period	Nash–Sutcliffe efficiency	Coefficient of determination	Percentage bias (%)
Calibration (1995–2008)	0.86	0.88	−0.8
Validation (2009–2020)	0.78	0.86	−12.4
Performance rating	Very good / Good	Very good	Very good / Satisfactory

Observed and Simulated Streamflow Patterns

The simulated hydrograph reproduced the monsoon rise and recessions in almost all years shown in figure 3. Good model reproduction of peak flow for wet years (2005 and 2018) with some individual monthly peaks overestimated. There was little dispersion of observed and simulated values around the one-to-one line in both periods figure 4, and more in the validation period at high flows.

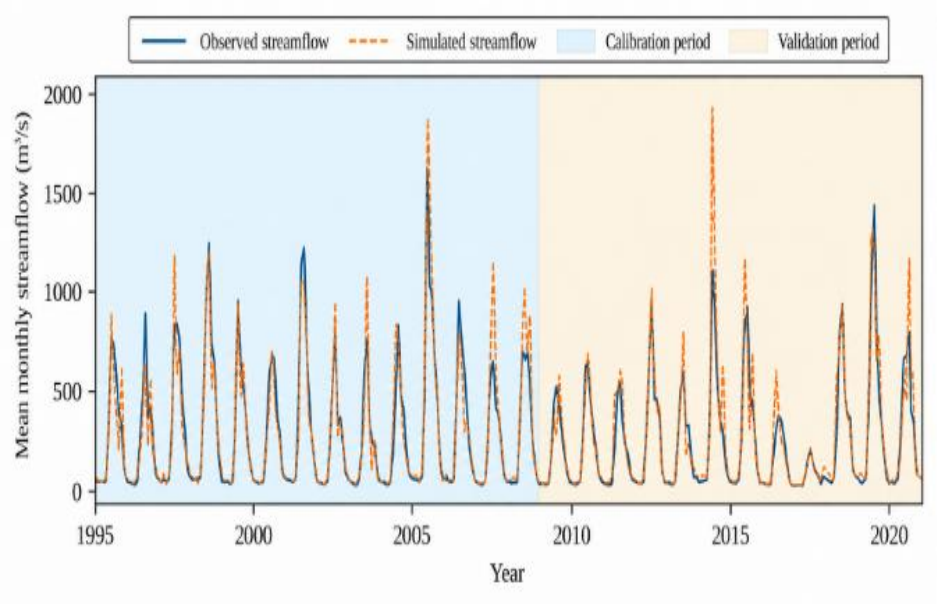


Figure 3: Observed and Simulated Monthly Streamflow

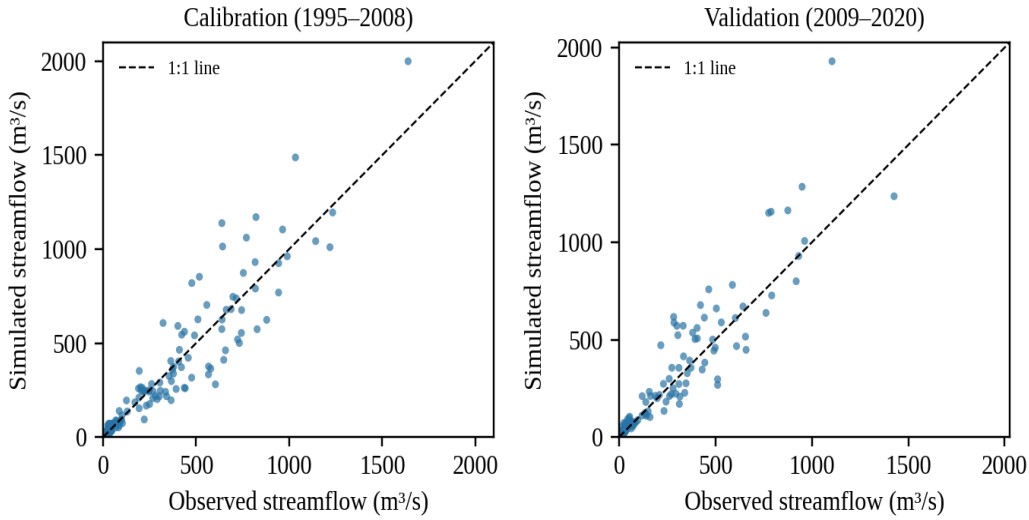


Figure 4: Streamflow Model Performance

Changes in Runoff and Freshwater Availability

The availability of fresh water clearly decreased during the two sub-periods. Mean annual runoff fell from 261 mm in 1991–2005 to 207 mm in 2006–2020, a decrease of 20.7%, and the mean annual water yield decreased from 9.40 to 7.47 billion m³. The flow duration curves moved to lower values on nearly all exceedance values figure 5. The high flow reference value was reduced from 817 to 642 m³/s, the median value from 150 to 99 m³/s, and the low flow reference value from 26 to 17 m³/s. This reduction was therefore highest for medians and low flows, where it is most critical for reliable supply and aquatic habitat.

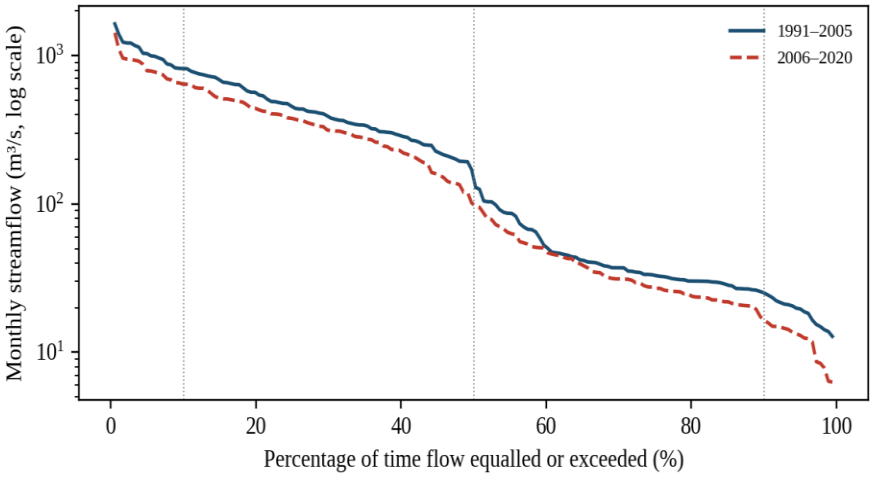


Figure 5: Monthly Streamflow Duration Curves

The results of seasonal analysis revealed that the southwest monsoon season provided approximately 73% of the annual water yield table 3 and figure 6. Maximum negative yield change was observed in the southwest monsoon (-1.46 billion m³). Yields during both seasons were already low and diminished by approximately 16-17%, limiting the water supply during the wettest and dried times of the year.

Table 3: Mean Seasonal Water Yield (billion m³) for the Two Sub-Periods

Season	1991–2005	2006–2020	Change (%)
Winter (Jan–Feb)	0.19	0.16	−15.8
Summer (Mar–May)	0.23	0.19	−17.4
Southwest monsoon (Jun–Sep)	6.87	5.41	−21.3
Northeast monsoon (Oct–Dec)	2.11	1.70	−19.4
Annual	9.40	7.47	−20.5

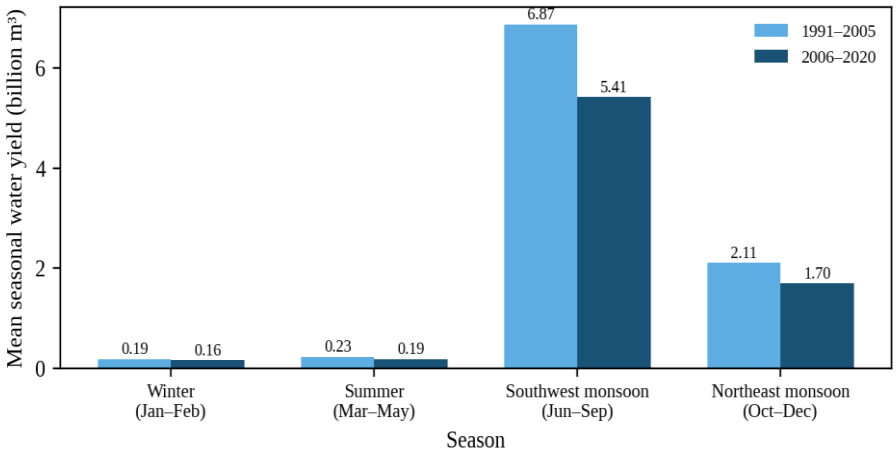


Figure 6: Mean Seasonal Water Yield at the Basin Outlet for 1991–2005 and 2006–2020

Relationship Between Climate Variability and Hydrological Response

There was a strong and positive correlation between annual run-off and annual rainfall (r=0.96). The relationship was non-proportional, with runoff decreasing by 20.7% for every 8.1% decrease in rainfall.

The warmer years typically fell below the fitted line at similar rainfall amounts suggesting that increased temperature led to more evaporative loss of precipitation, resulting in less streamflow.

Identification of High- and Low-Water Availability Periods

The high-availability time period shifted from July to October, with flows often being above the median for that month. The low flow window included January-May, when low flows occurred in most recent years below the 90% exceedance level. The runoff in 2005 was the highest (397 mm), and in 2017 was the lowest (51 mm) among the years. The second sub-period experienced the clustering of more dry years particularly in 2009, 2011, 2016 and 2017, and the back-to-back deficits in 2016 and 2017 resulted in the longest two-year dry spell in the record.

Implications for Freshwater-Resource Sustainability

Basin-wide reduction in median flow and lower dry season yield with increasing frequency of dry years suggests a decreased reliability of supply while the basin still receives significant monsoon rainfall. Water allocation rules and reservoir operating plans prior to 2005 are likely to overestimate the amount of water which can be delivered with reliability. Low flows also pose the risk of not providing the minimum flow necessary to sustain riparian habitat, dissolved oxygen, and fish migration during the peak summer months.

V. Discussion

Interpretation of Major Hydrological Findings

The results have shown that the hydrological system for the basin has reacted strongly to relatively modest climatic variations. The increase in the difference between runoff and rainfall is due to threshold response and occurs on catchments where soils and aquifers need to be filled to produce significant streamflow. As precipitation decreases, more may stay in the soil to satisfy soil moisture and evaporative demand and less becomes available to the river.

Sustainable Water-Management Strategies

The findings suggest a number of strategies. Deficit monsoons can lead to modifications of reservoir rule curves to increase carry-over storage. Check dams, tanks and recharge wells can be used to manag recharge aquifers with a portion of the high monsoon flow to be stored for use during the dry season. Droughts can alleviate pressure from either source of water through conjunctive use. The current and future protection and maintenance of minimum ecological flows are appropriate, especially in January-May to maintain aquatic biodiversity and water quality.

Practical Implications for Water Managers and Policymakers

Calibrated models and flow duration indicators can be utilized as operational tools for seasonal forecasting and preparedness for droughts by water managers. Allocation rules can be tied to the performance of the monsoon by flexible sharing rules that allocate the deficit in a proportionate manner. Investments in demand side measures like micro irrigation, change in land use away from water-consuming crops and minimizing distribution losses in urban areas provide a sustainable, low-cost approach to vulnerability reduction. Increased monitoring networks and open data exchange would enhance coordination efforts at the basin level.

Study Limitations

There are some restrictions to be noted. This gridded temperature information is low resolution and may not resolve sub-regional variations in the headwater region of mountains. Furthermore, reservoir operations were added, which included reported monthly releases, thereby removing the daily operation decisions and could result in a levelling of the day-to-day operations and/or obscure extreme peak anomalies during periods of extreme wet or dry. Reported monthly releases were used to represent reservoir operations, as

this may not reflect daily operating decisions. The impact of land use and groundwater extraction on the study period has not been explicitly separated from climatic effects. Lastly, historical conditions were considered and future projections under climate scenarios were not included. In addition, the change in agricultural practices, cropping patterns, and groundwater abstraction rates over the 30-year period were not explicitly differentiated from climatic effects, so it is important to consider this 20.7% reduction in runoff a response to both climate variability and the effects of unquantified human drivers.

VI. Conclusion

This study involved a semi-distributed hydrological model along with climate variability analysis to estimate freshwater availability in the upper Cauvery river basin during the period (1991-2020). The model was found to be adequate for the analysis of observed streamflow, as the model reproduced the observed streamflow well for both calibration and validation. The mean annual temperature showed a strong amplification, with an increase of approximately 0.27 °C per decade between the two sub-periods; mean annual rainfall showed a relatively weak positive amplification, with a decrease of 8.1% between the two sub-periods; mean annual runoff showed a strong negative amplification, with a decrease of 20.7% between the two sub-periods. Median and low flows reduced by approximately a third, more dry years after 2005, and annual water yield was reduced from 9.40 to 7.47 billion m^3. Hydrological modeling was found to be an important tool to help convert climate signals into meaningful indicators of water availability, to identify specific periods, or seasons, of excess and deficit, and to provide support for evidence-based management. Key recommendations are the incorporation of new hydrological baselines, adjustments to the operation of reservoirs to increase carry-over storage, increased managed aquifer recharge, conjunctive use of surface water and groundwater, and protecting minimum ecological flows and flexible allocation policies for deficit years. The variability in climate examined was the dominant factor, but the changes were also the result of unquantifiable contributions from changes in land use and localized groundwater extraction during the study period. Future studies could consider downscaled climate projections to assess the availability under future scenarios, disaggregating land-use change and groundwater pumpage from climatic drivers, incorporating water-quality and ecological indicators and evaluating hybrid approaches that combine process-based models with data-driven approaches to enhance modeling of extreme high and low flows.

References

[1] Rodell, M., & Li, B. (2023). Changing intensity of hydroclimatic extreme events revealed by GRACE and GRACE-FO. *Nature Water*, *1*(3), 241-248. https://doi.org/10.1038/s44221-023-00040-5

[2] Gudmundsson, L., Boulange, J., Do, H. X., Gosling, S. N., Grillakis, M. G., Koutroulis, A. G., ... & Zhao, F. (2021). Globally observed trends in mean and extreme river flow attributed to climate change. *Science*, *371*(6534), 1159-1162. https://doi.org/10.1126/science.aba3996

[3] Stevenson, S., Coats, S., Touma, D., Cole, J., Lehner, F., Fasullo, J., & Otto-Bliesner, B. (2022). Twenty-first century hydroclimate: A continually changing baseline, with more frequent extremes. *Proceedings of the National Academy of Sciences*, *119*(12), e2108124119. https://doi.org/10.1073/pnas.2108124119

[4] Zhang, Y., Zheng, H., Zhang, X., Leung, L. R., Liu, C., Zheng, C., ... & Blöschl, G. (2023). Future global streamflow declines are probably more severe than previously estimated. *Nature Water*, *1*(3), 261-271. https://doi.org/10.1038/s44221-023-00030-7

[5] Mishra, V., Thirumalai, K., Jain, S., & Aadhar, S. (2021). Unprecedented drought in South India and recent water scarcity. *Environmental Research Letters*, *16*(5), 054007. https://doi.org/10.1088/1748-9326/abf289

[6] Aadhar, S., & Mishra, V. (2021). On the occurrence of the worst drought in South Asia in the observed and future climate. *Environmental Research Letters*, *16*(2), 024050. https://doi.org/10.1088/1748-9326/abd6a6

[7] Ficklin, D. L., Null, S. E., Abatzoglou, J. T., Novick, K. A., & Myers, D. T. (2022). Hydrological intensification will increase the complexity of water resource management. *Earth's Future*, *10*(3), e2021EF002487. https://doi.org/10.1029/2021EF002487

[8] Hirabayashi, Y., Tanoue, M., Sasaki, O., Zhou, X., & Yamazaki, D. (2021). Global exposure to flooding from the new CMIP6 climate model projections. *Scientific reports*, *11*(1), 3740. https://doi.org/10.1038/s41598-021-83279-w

[9] Slater, L. J., Anderson, B., Buechel, M., Dadson, S., Han, S., Harrigan, S., ... & Wilby, R. L. (2020). Nonstationary weather and water extremes: a review of methods for their detection, attribution, and management. *Hydrology and Earth System Sciences Discussions*, *2020*, 1-54. https://doi.org/10.5194/hess-25-3897-2021

[10] Brunner, M. I., Slater, L., Tallaksen, L. M., & Clark, M. (2021). Challenges in modeling and predicting floods and droughts: A review. *Wiley Interdisciplinary Reviews: Water*, *8*(3), e1520. https://doi.org/10.1002/wat2.1520

[11] Nearing, G. S., Kratzert, F., Sampson, A. K., Pelissier, C. S., Klotz, D., Frame, J. M., ... & Gupta, H. V. (2021). What role does hydrological science play in the age of machine learning?. *Water Resources Research*, *57*(3), e2020WR028091. https://doi.org/10.1029/2020WR028091

[12] Nearing, G., Cohen, D., Dube, V., Gauch, M., Gilon, O., Harrigan, S., ... & Matias, Y. (2024). Global prediction of extreme floods in ungauged watersheds. *Nature*, *627*(8004), 559-563. https://doi.org/10.1038/s41586-024-07145-1

[13] Hammond, J., Anderson, B., Simeone, C., Brunner, M., Muñoz-Castro, E., Archfield, S., ... & Armitage, R. (2025). Hydrological whiplash: Highlighting the need for better understanding and quantification of sub-seasonal hydrological extreme transitions. *Hydrological Processes*, *39*(3), e70113. https://doi.org/10.1002/hyp.70113