Hydrological Modeling of Groundwater and Surface Water Interactions in Response to Anthropogenic Climate Variability

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Abstract: Purpose: This study examines the relationship between groundwater and surface water in the Amaravathi River Basin, India, due to anthropogenic variability in climate factors. Methodology: A coupled SWAT-MODFLOW model has been developed based on publicly available data sets, such as data on meteorological, hydrological, land use, and climate projection data. The simulations of future climate scenarios were carried out using SSP2-4.5 and SSP5-8.5 pathways in the period of 2025-2060. Statistical indicators that were used to perform model calibration and validation include Nash Sutcliffe Efficiency (NSE), Root Mean Square Error (RMSE), and Coefficient of Determination (R^2). Results: The results show that under SSP2-4.5 and 17.9% under SSP5-8.5, there is a significant increase in surface runoff compared to the period before the change. On the contrary, the area of groundwater recharge reduces by 8.5% and 16.9%, respectively. Under high-emission conditions, there is a decrease in baseflow contribution, by 42 % to 34 %, which indicates a weakened groundwater-surface water connection. The performance of the models was good with a range of NSE values between 0.72 and 0.85 and high values (greater than 0.75) of R^2. Conclusion: The research shows that climate variability will result in a transition to hydrological regimes dominated by runoffs, reducing groundwater sustainability and vulnerability of systems. The integrated modeling framework can give essential information on how climate-resilient water management strategies are developed.

Keywords: Hydrological Modeling; Groundwater Interaction; Climate Variability; SWAT-MODFLOW; Water Sustainability; Runoff Dynamics.

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I. Introduction

The complex pressures compared to the natural processes in water resources systems are increasingly subjected to the complex pressures of anthropogenic climate variability, which change the natural dynamics of hydrological processes. The interaction between surface water and groundwater is one of these, as it forms a vital part of the hydrological cycle, regulating water supply, the sustainability of the ecosystem, and water security. Surface water and groundwater do not exist in isolation, but instead, hydraulic interactions exist between these two water bodies (Banerjee & Ganguly, 2023).

The anthropogenic climate variability, coupled with greenhouse gas emissions, land-use alterations, and urban growth, has had a substantial impact on hydrological regimes in the world. The changes in the intensity of precipitation, temperature variations, and the rate of evapotranspiration directly influence the processes of surface runoff as well as subsurface recharge. The latter is especially high in semi-arid and developing countries where the water resources are already stressed and extremely reliant on climate-sensitive recharge systems (Davamani et al., 2024).

Recent research has highlighted that effects of climate change are not linear and may lead to nonlinear responses of hydrological systems. An example of this is the possibility that altered rainfall patterns might lead to higher surface runoff and, at the same time, reduced groundwater recharge since there would be fewer infiltration opportunities (Al-Hasani et al., 2023). On the same note, an increase in temperature increases evapotranspiration, further reducing the availability of water in the surface and underground reservoirs (Ngo et al., 2024).

The interdependence between groundwater and surface water systems requires integrated modeling systems in order to better describe the interactions between the two systems in the changing climatic conditions. Conventional hydrological research tended to analyze these systems separately and therefore generated fragmented knowledge on these systems and poor water management measures. But now it is possible to dynamically simulate the coupled processes by using integrated modeling frameworks that can provide more insight into the behavior of the system under future climate conditions (Soltani et al., 2023).

Although there have been improvements in hydrological models, there are still a number of obstacles. These include the uncertainty in future climate predictions, the lack of long-term hydrological data, and the difficulty posed by representing the anthropogenic impact, such as groundwater extraction and the change in land use. Moreover, the need to expressly incorporate the climate variability in the hydrological models to increase the predictive power and relevance of the policies is increasing.

This study aims at contributing to the solution of such problems by developing a fully integrated hydrological modeling system to understand the interactions between groundwater and surface water within anthropogenic climate variability. The research is geared towards the maximization of knowledge on the hydrological responses to the climate drivers and providing a scientific basis for the sustainable utilization of the water resources.

Paper Organization

This paper has been subdivided into six big sections. Section 1 presents the research problem, objectives, and significance of researching interactions between groundwater and surface water during anthropogenic climate variability. In Section 2, a comprehensive literature review is provided that outlines the key developments in this area, development models, and gaps in the literature. Section 3 explains the methodology, which includes the study area, data sources, integrated SWAT-MODFLOW modeling framework, climate scenarios, and study analysis. In section 4, the results of the simulations are presented in a quantitative analysis, tables, and graphical representation. Section 5 gives a detailed discussion of the findings and their implications on the hydrological processes as well as managing the water resources. Lastly, the summation of the main insights of the study is expressed with the help of Section 6, which summarizes the main insights of the study, addresses the contributions, and recommends the directions of the future research.

II. Literature Review

The discipline of studying groundwater-surface water interactions has undergone a considerable change in the past decades, moving away from the conceptual frameworks and taking on the advanced numerical modeling approaches. Learning about hydraulic connectivity between aquifers and surface water bodies, which mainly involves the contribution of baseflow, bank storage, and dynamics of infiltration, preoccupied much of the early research. In a careful study, it is observed that these interactions are important in securing a hydrological equilibrium and ecological integrity (Banerjee & Ganguly, 2023).

The recent studies have been widely using integrated modeling methods to model the coupled hydrological systems. To illustrate this point, watershed-scale model studies have shown that coupled surface water and groundwater processes are a more accurate representation of hydrological responses to changes in environmental conditions. Catchment-scale modeling shows that combined models are much more effective in predicting streamflow and groundwater levels than are standalone models (Gobezie et al., 2023).

Spatial studies also indicate that there is spatial variation of groundwater and surface water interactions. Studies in the temperate areas reveal that seasonal variations greatly affect the nature and magnitude of water movement between the rivers and the aquifers. Such results highlight the need to take into account the climatic and geological heterogeneity in order to model hydrological systems (Duque et al., 2023).

Climate change has become one of the most overwhelming factors that affect the hydrological processes and, therefore, the evaluation of the water resources. Research evaluating climate effects on elements of water balance illustrates that elevated temperature and the change in precipitation patterns result in substantial shifts in evapotranspiration, runoff, and recharge rates. The models of integrated groundwater-surface water have been successfully employed to measure these effects, and these systems have been shown to be highly sensitive to climate variability (Soltani et al., 2023).

Future studies put more focus on the susceptibility of the coupled hydrological systems to climate change in headwater catchments and ecologically sensitive areas. The results have shown that even slight climatic changes can cause imbalance in surface and underground flows, and this imbalance can result in reduced base flow and in altered stream regimes (Munir et al., 2024). These disturbances have extensive ramifications on water resources and the health of ecosystems.

Critical analysis of the impacts of climate changes on groundwater resources reveals that some of the main challenges include reduced rate of recharge and increased groundwater depletion, as well as increased uncertainty in hydrological projections. Simulation models are being instrumental in overcoming these challenges by providing the ability to analyze a scenario and predict in the long run (Davamani et al., 2024).

Also, investigations of climate models point to uncertainties in climate model predictions, especially in areas such as the Mediterranean basin, where there is variability in climate model projections, leading to divergent hydrological results. These uncertainties render the decision-making processes more complicated and highlight the importance of well-developed modeling structures that incorporate the analysis of uncertainties (Noto et al., 2023).

The studies conducted on groundwater recharge in the future climate conditions prove that hydrological modeling is a crucial tool to be used to comprehend the dynamics of recharge. Research indicates that the recharge rate is extremely sensitive to the alterations of rainfall intensity and distribution of land uses, with important implications on groundwater sustainability (Ngo et al., 2024).

In the same way, the studies of arid and semi-arid areas show that climate change is a powerful factor influencing access to surface water. The modeling techniques that have incorporated the regional climatic projections with the hydrological models have shown that will experience a decrease in the streamflow and an increase in the frequency of extreme events, which will pose a challenge to the management of water resources (Al-Hasani et al., 2023).

Lastly, the use of modeling tools like water evaluation and planning systems has been used to complement the overall water resource management strategies. These tools allow us to fully evaluate the effects of climate change on water supply and demand to make informed decisions and sustainable management practices (Cacal et al., 2024).

Although there is extensive progress, there are still gaps in the literature. These are a low level of integration of anthropogenic factors, including land-use change and abstraction of groundwater; a lack of focus on uncertainty quantification; and a lack of region-specific studies in developing countries. The only way of taking care of these gaps is through sophisticated modeling systems involving a combination of climate projections, hydrological processes, and human interventions.

III. Methodology

This study uses combined hydrological modeling to simulate and analyze groundwater-surface water interactions under conditions of anthropogenic climate variability. The methodology is designed into six major parts, which are study area characterization, data acquisition, model development, climate scenario generation, calibration and validation, and analytical assessment.

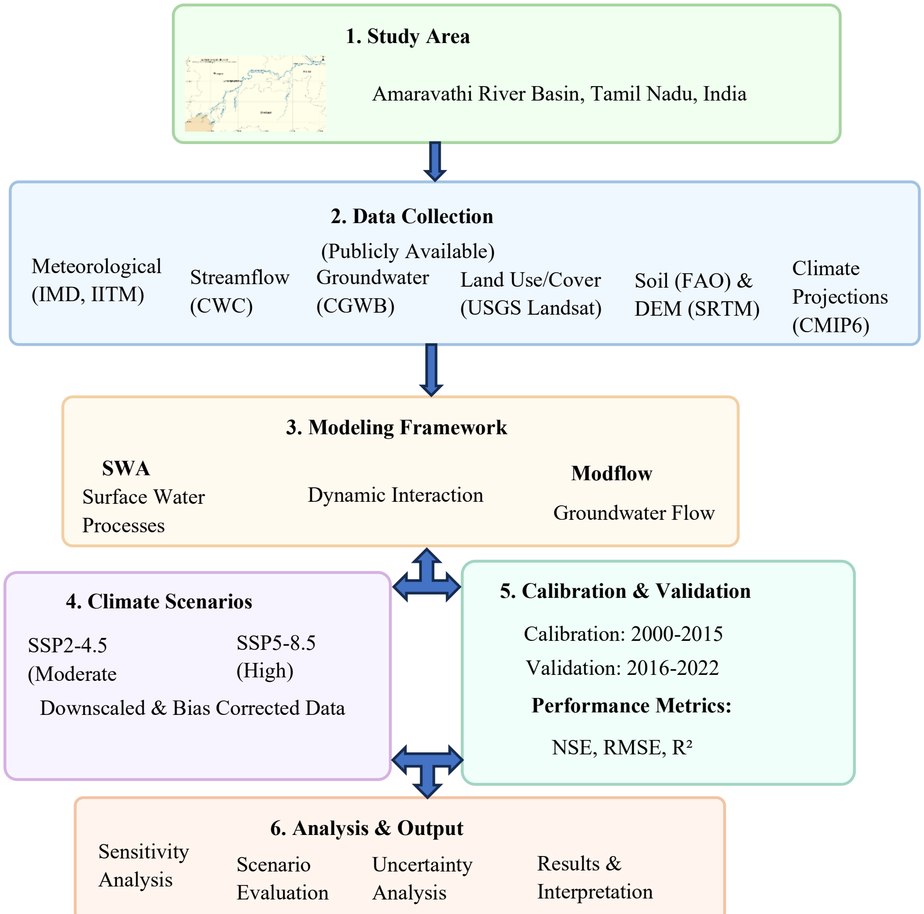

Figure 1: Integrated Methodology Flow Diagram for Groundwater–Surface Water Interaction Modeling Under Climate Variability

Figure 1 shows the general methodological outline used in this study, which starts with the selection of the Amaravathi River Basin as the study area and then the collection of publicly available data sets such as meteorological, hydrological, land use, soil, and climate projection data. The model then combines the surface and subsurface hydrological processes in a coupled SWAT-MODFLOW modeling scheme to simulate the dynamic interaction between the groundwater and surface water systems. Climate variability is integrated with SSP2-4.5 and SSP5-8.5 scenarios, and the model is calibrated and validated with statistical performance indicators. Lastly, the framework conducts sensitivity, scenario, and uncertainty analysis to come up with insights on the hydrological responses to changing climatic conditions.

3.1 Study Area

The research is done in the Amaravati River Basin, which is a major tributary of the Cauvery River, which is located in Tamil Nadu, India. The basin spreads across districts that include Tiruppur, Karur, and Dindigul, with an approximate area of 8,500 km². It has a semi-arid to sub-humid tropical climate with an annual rainfall ranging between 600 mm and 900 mm, mainly brought about by the southwest as well as the northeast monsoons. The basin has a variety of land-use practices such as agriculture, urban settlements, and forested areas, making it quite suitable for studying the anthropogenic effects on the hydrological processes. The geology is mainly comprised of the hard rock formations, and this contributes to low storage of groundwater and high reliance on seasonal recharge. The basin is a perfect site to study the interactions between groundwater and surface water in the face of climate variability since the surface water bodies such as reservoirs, tanks, and river networks are hydraulically connected with shallow aquifers.

3.2 Data Sources

To guarantee transparency and reproducibility, publicly available datasets are used in the current study. Daily precipitation, temperature, and evapotranspiration are meteorological data that are obtained by the India Meteorological Department (IMD) and supplemented with gridded data derived by the Indian Institute of Tropical Meteorology (IITM). The source of data of streamflow in the Amaravathi River is the Central Water Commission (CWC), and the source of groundwater level data is the Central Ground Water Board (CGWB) observation wells that are located within the basin. The satellite data is used to derive land use and land cover data, and soil data is derived using the FAO harmonized world soil database. The data of the Digital Elevation Model (DEM) with the resolution of 30 m is based on the Shuttle Radar Topography Mission (SRTM) data. The data on climate projections of the future are obtained through the Coupled Model Intercomparison Project Phase 6 (CMIP6) archive and are consistent with the international standards of climate modeling.

3.3 Modeling Framework

To obtain an integrated hydrological modeling framework, the Soil and Water Assessment Tool (SWAT) that is used in simulating the surface hydrological processes is coupled with the MODFLOW that is used in simulating the groundwater flow. SWAT is used to model watershed processes like surface runoff, infiltration, evapotranspiration, and soil moisture dynamics, whereas MODFLOW models subsurface flow, aquifer recharge, and movement of groundwater. The coupling is created by a dynamic exchange of recharge and baseflow parameters and enables two-way interaction between the surface water and groundwater systems. The model setup consists of delimiting watersheds using DEM data, classifying the units of the hydrological response on the basis of the land use and soil properties, and discretizing the aquifer system into grid cells. The combined framework enables continuous simulation of hydrological processes in different climatic and anthropogenic conditions.

3.4 Climate Variability Scenarios

To measure the effect of anthropogenic climate variability, future climate scenarios are created based on downscaled output of CMIP6 models under two representative emission pathways, SSP2-4.5 (moderate scenario) and SSP5-8.5 (high-emission scenario). The bias correction schemes like quantile mapping are used to tune the model outputs to agree with historical data. The scenarios take into consideration the changes in temperature, the intensity of precipitation and the distribution of the seasons over the period 2025 to 2100. Such projections are factored into the SWAT-MODFLOW framework to model the future hydrological response, analyze the long-term trends in groundwater recharge, surface runoff and system interactions.

3.5 Model Calibration and Validation

To make sure that the integrated model is reliable and accurate, the hydrological data is observed and the integrated model is calibrated and tested. The period 2000-2015 is the one to be calibrated, and 2016-2022 is the period, which is to be validated. Some of the parameters to be adjusted in a combination of both manual calibration and automated optimization methods are key parameters like curve number, hydraulic conductivity, baseflow recession constant, and aquifer storage properties. Statistical measures are the basis of measures of model performance, which include Nash-Sutcliffe Efficiency (NSE), Root Mean Squared Error (RMSE), and Coefficient of Determination (R^2). Where the values of NSE exceed 0.7, the values of RMSE are maintained to a minimum with the values of R^2 high, indicating that there is a strong correlation between observed and simulated data.

3.6 Analytical Techniques

The analysis is done by a sensitivity analysis, a scenario analysis, and quantification of uncertainty to gain an idea about the level of soundness of the modeling framework. Sensitivity analysis is conducted to find out some crucial parameters of the interactions between the ground water and surface water. To analyze the alterations of the hydrological components, the alterations of the natural conditions are compared to the future climate forecast in the form of the scenario analysis. The analysis of uncertainty is done through Monte Carlo simulation whereby a series of model runs are executed using different sets of parameters to determine how much the possible results can vary. This broad, analytical approach will provide results with such deterministic tendencies and also probabilistic variability of hydrological responses.

IV. Results

The SWAT-MODFLOW modeling system generated in-depth evidence of the hydrological behavior of the Amaravathi River Basin under the conditions of baseline and future climate. The outcomes are concerned with some essential elements that include surface runoff, groundwater recharge, and the interactions between groundwater and surface water.

4.1 Hydrological Component Analysis

The outcomes of the simulation show that there are major differences in the hydrological components in various climate conditions. In the high-emission scenario (SSP5-8.5), surface runoff demonstrates the increasing trend because of the increasing rainfall events, and groundwater recharge illustrates the declining trend because of the decreasing rainfall events. On the other hand, the moderate scenario (SSP2-4.5) is relatively stable in its hydrological response, characterized by moderate variations.

Table 1: Summary of Hydrological Changes Under Climate Scenarios

Hydrological Component	**Baseline (2000–2020)**	**SSP2-4.5 (2040–2060)**	**SSP5-8.5 (2040–2060)**
Annual Runoff (mm)	312	335 (+7.4%)	368 (+17.9%)
Groundwater Recharge (mm)	142	130 (−8.5%)	118 (−16.9%)
Baseflow Contribution (%)	42	38 (−9.5%)	34 (−19.0%)
Evapotranspiration (mm)	890	925 (+3.9%)	970 (+9.0%)

According to table 1, surface runoff is expected to grow considerably in the future, especially in the case of SSP5-8.5, in which there is a 17.9% increase in surface runoff compared to the baseline. Conversely, groundwater recharge decreases by 16.9%, and this implies that the groundwater is able to infiltrate less. The contribution of baseflow to river systems is also reduced to indicate a decrease in connectivity between the surface water and the ground water. Increased water loss through evapotranspiration further increases the loss of water, emphasizing the effect of rising temperatures on hydrological processes.

4.2 Groundwater–Surface Water Interaction

The coupled model indicates that the contribution of groundwater to streamflow (baseflow) decreases in the future under the climate conditions. In dry seasons, the rivers' flow will be more of direct runoff than of long-term discharge of groundwater. This implies that it has shifted towards more short-lived flow conditions, particularly in situations where high emissions are observed.

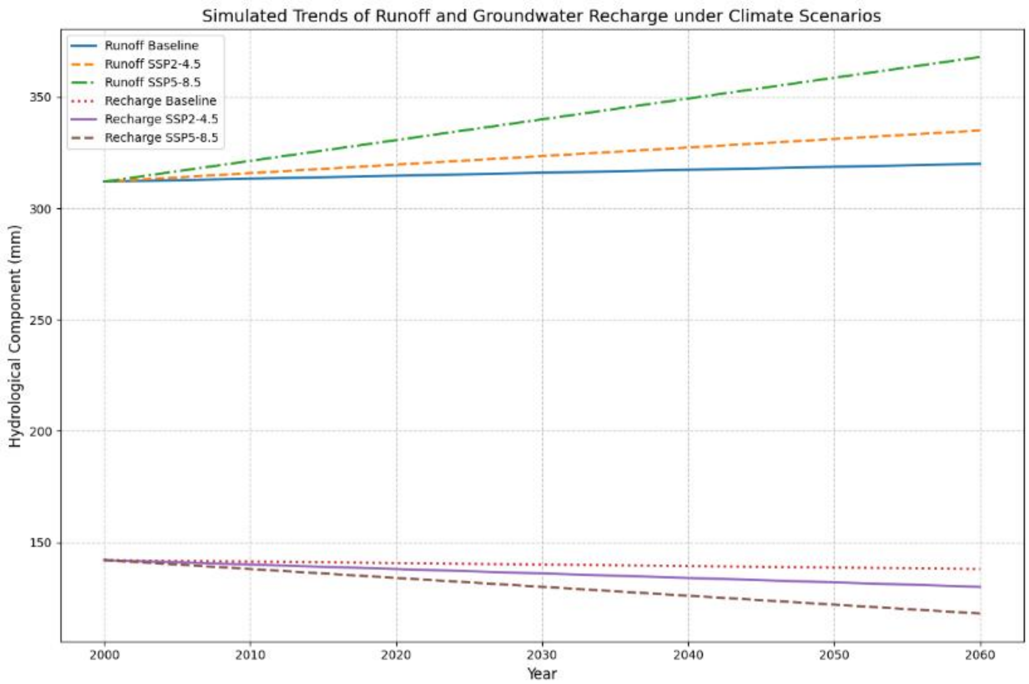

Figure 2: Simulated Trends of Runoff and Groundwater Recharge Under Climate Scenarios

In figure 2, the trends plotted clearly show that there are divergent trends between surface run-offs and ground water recharge. Runoff reveals that the trend is on the increase with time, especially where the SSP5-8.5 is indicated, representing increased events of precipitation. Conversely, the groundwater recharge has been on a downward trend, meaning that there are less infiltration and more evapotranspiration losses. The runoff minus recharge ratio increases more after 2040, highlighting the increasing imbalance in the hydrological processes with the climate variability.

4.3 Model Performance

The calibration and validation of results of the model prove the high level of predictive power. The values of Nash-Sutcliffe Efficiency (NSE) were between 0.72 and 0.85, and R^2 values were greater than 0.75 in both streamflow and groundwater level. The values of RMSE were in an acceptable range, meaning that there was a little variation between real and simulated data.

5 Discussion

The findings of this research point to the fact that anthropogenic climate variability plays the crucial role in the dynamics of a coupled system of groundwater and surface water systems in the Amaravathi River Basin. The fact that the proportion of precipitation turned into instant runoff and not a part of subsurface storage reflects a fundamental change in the hydrological division where a higher percentage of precipitation is transformed into instant runoff instead of it being converted into groundwater recharge. This change can be explained by the increasing rainfall events, an increase in temperature, and other related increases in evapotranspiration, which reduce the effective infiltration capacity of the soil system. As it is shown in table 1 and figure 2, even in the conditions of high emission, the divergence between runoff and recharge increases, which means that there is a progressive imbalance in the hydrological cycle.

The decreasing rate of groundwater recharge has dire consequences on long-term water security, especially in semi-arid areas where groundwater is one of the major sources of water to irrigate and supply domestic water needs. These findings suggest that the integrated modeling framework is relevant to examine the hydrological changes associated with climate.

The general conclusion is that the anthropogenic climatic variability has great impacts on the balance existing between the groundwater systems and surface water systems and increases the runoff, reduces the recharge, and weakens the hydrological connections. It will also be essential to enhance the hydrological monitoring networks and enhance access to the high-resolution data to help refine the model predictions and support the evidence-based decision-making.

In general, this research adds to the existing body of knowledge on climate-induced hydrological changes by showing how the anthropogenic variability changes the balance between the systems of groundwater and surface water. The knowledge gained from this study is a scientific basis for the formulation of sustainable and resilient water management concepts in the face of the current climate change.

6 Conclusion

This study will provide a detailed evaluation of the interaction of groundwater and surface water under anthropogenic climate variability in an integrated SWAT-MODFLOW modeling platform in the Amaravathi River Basin. The results indicate that there will be a great change in the hydrological processes, where surface runoff will increase and groundwater recharge will decrease under future climatic conditions. The rate of runoff is estimated to increase by 7.4% under SSP2-4.5 and 17.9% under SSP5-8.5, where groundwater recharge is expected to decline by 8.5 and 16.9, respectively. Also, the contribution of baseflow decreases to 34-38%, showing less connectivity between groundwater and surface water. These changes point to the shift towards a runoff-dominated hydrological regime, which can cause water scarcity during dry seasons and increase their exposure to extreme hydrological events. The decrease in the recharge of the groundwater is especially critical to the semi-arid regions, where the groundwater is a primary source of agricultural and domestic needs. The consistency of the integrated model in the ability to reflect complicated hydrological processes is confirmed by the performance of the validated model (NSE: 0.72–0.85; $R^2 > 0.75$). The study highlights the need to adopt water resource management approaches that include surface and subsurface processes. To reduce the effects of the above effects, there is a need to have sustainable interventions in the form of artificial recharge, watershed management, and climate-resilient planning. On the whole, the presented research can serve as an insightful contribution to the policymaking process and water management systems development, as these studies can be used to develop adaptive and sustainable water management models in the framework of climate change.

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