



RESEARCH ARTICLE

Decision support system for climate-resilient runoff estimation

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Abstract

This study addresses the critical need for climate-resilient hydrological tools by developing Decision Support System (DSS). The DSS integrates a modified Soil Conservation Service Curve Number (SCS-CN) method with high-resolution geospatial datasets, such as Sentinel-2 Land-Use/Land-Cover (LULC), OpenLand soil properties, Shuttle Radar Topography Mission (SRTM)- Digital Elevation Model (DEM) topography and Climate Hazards Group Infrared Precipitation with Station (CHIRPS) precipitation, to simulate historical and near-real-time runoff. Furthermore, it incorporates CMIP6 climate projections to facilitate future runoff estimation. Validated across two contrasting Indian watersheds-the monsoon-driven Salebhata catchment ($R^2 = 0.82$) and semi-arid Venkatapur sub-watershed ($R^2 = 0.78$). The model performs well at capturing seasonal variability, including monsoon floods, runoff during dry spells, seasonal extremes and variations across different areas. Its user-friendly application enables stakeholders to create real-time, location-specific runoff estimates through polygon-based analysis, which directly facilitates flood forecasting and adaptive water resource management. By incorporating climate projections and high-resolution geospatial analysis, this framework provides a reproducible platform for climate-resilient water resource planning, especially in data-poor regions exposed to hydroclimatic extremes.

Keywords: climate change; CMIP6 climate projections; hydrological modelling; runoff modelling

Introduction

Surface runoff, a keystone component of the hydrological cycle, governs flood hazard, water resource sustainability and infrastructure resilience (1). The intensification of rainfall extremes, driven by climate change and accelerating urbanization, has increased hydrological uncertainty. Therefore, adaptive measures for runoff estimation have become essential (2). Traditional methods, which depend on historical rainfall data, are inadequate in capturing the non-stationary hydrological behavior induced by anthropogenic influences (3). The soil SCS-CN method introduced in the 1950s, remains widely adopted for its simplicity and minimal data requirements (4). This empirical model estimates runoff using the Curve Number (CN) derived from land use, soil type and Antecedent Moisture Conditions (AMC). However, the SCS-CN method exhibits critical limitations. It oversimplifies spatial variation by assuming uniform rainfall distribution and neglecting microtopographic and land-use heterogeneity (5). Additionally, its static land-use classifications, such as broad categories like "agriculture," fail to capture dynamic changes, including urbanisation or crop rotation (6). This method also neglects the effects of slope, which can alter runoff coefficients on steep terrains and require slope-adjusted CN values.

Remote sensing and geospatial technologies now enable high-resolution modeling. Sentinel-2 imagery supports precise LULC classification, essential for dynamic CN adjustments. OpenLand soil datasets and SRTM topography enhance spatial accuracy, particularly in regions with expansive vertisols (e.g., black cotton soils), which exhibit nonlinear runoff responses due to shrink-swell behavior (6). Integrating these datasets with climate projections from the CMIP6 IITM-ESM model under the SSP245 scenario allows for simulations of future runoff, addressing a key gap in traditional methods (7).

Cloud-based DSS represents a step forward in hydrological planning. The systems take multi-source data (LULC, soil, climate) and convert them into easy-to-use interfaces, providing real-time runoff estimation (8). For instance, in semi-arid regions such as India's Deccan plateau, DSS tools empower stakeholders to optimize water-harvesting strategies amid erratic monsoons (9). By combining climate science, geospatial analysis and stakeholder requirements, DSS models democratize adaptive water management in data-scarce areas (10).

Materials and Methods

Study area

The study encompasses two distinct hydrological regions: the Salebhata catchment and the Venkatapur sub-watershed. The Salebhata catchment (4588.9 km²) lies within the Mahanadi River Basin of Odisha and Chhattisgarh districts. The region has a tropical monsoon climate with 1350–1500 mm of rainfall annually, which predominantly occurs during the June–September monsoon season (11). The catchment includes agricultural land, forest cover and urban areas, with undulating topography ranging from 200–650 m above mean sea level. Venkatapur sub-watershed (685 km²) is located in the Krishna River basin of Raichur district, Karnataka. This semi-arid region receives 650–750 mm of rainfall annually and comprises black cotton soils (vertisols). The locations range from 450–700 m in elevation, with dominant rainfed agriculture and the cultivation of cotton, green gram and sorghum. These regions were selected for their contrasting hydrological conditions, diverse land-use patterns and varied soil characteristics, providing suitable test environments for the decision support system's application across different geographical areas.

Methodology

This study estimates runoff using the modified soil SCS-CN method, incorporating remote-sensing data on soil properties, LULC, topography and rainfall. The methodology used to estimate runoff is outlined below, including the derivation of the runoff equation, Antecedent Moisture Condition (AMC) adjustments and slope correction. The datasets used in this study are summarized in Table 1.

The runoff estimation process begins with the basic water balance equation:

$$P = I_a + F + Q \quad (\text{Eqn. 1})$$

Where:

P = total precipitation (mm)

I_a = initial abstraction (mm)

F = infiltration (mm)

Q = runoff (mm)

This equation is followed by two proportional equality hypotheses to relate runoff to infiltration and retention:

$$\frac{Q}{P - I_a} = \frac{F}{S} \quad (\text{Eqn. 2a})$$

$$I_a = \lambda S \quad (\text{Eqn. 2b})$$

Where, S is the potential retention (mm) and $\lambda=0.2$ is an empirical coefficient. The runoff Q is then calculated as:

$$Q = \frac{(P - 0.2S)^2}{P + 0.8S} \quad (\text{Eqn. 3})$$

The potential retention S is related to the CN by:

$$S = \frac{25400}{CN} - 254 \quad (\text{Eqn. 4})$$

Adjustments for AMC

The CN is calculated for AMC II (normal conditions) and adjusted for AMC I (dry) and AMC III (wet) conditions (17). The AMC thresholds for daily rainfall are as follows:

AMC I (dry condition): Typically, when the 5-day antecedent rain is less than 25 % of the CN-specific value.

AMC II (normal condition): When the 5-day antecedent rainfall is between 25 % and 50 % of the CN-specific value.

AMC III (wet condition): When the 5-day antecedent rainfall exceeds 50 % of the CN-specific value.

The CN values for these conditions are modified using the following equations:

$$CN_I = \frac{CN_{II}}{2.281 - 0.01281 \times CN_{II}} \quad (\text{Eqn. 5})$$

$$CN_{III} = \frac{CN_{II}}{0.427 + 0.00573 \times CN_{II}} \quad (\text{Eqn. 6})$$

Slope-based adjustment for AMC II

For areas with steep terrain, the CN for AMC II is further adjusted using a slope correction factor. The slope-adjusted CN for AMC II (SACN2) is given by the standardized formula (18).

$$SACN2 = \frac{1}{3}(CN3 - CN2) - (1 - 2e^{-13.86\alpha}) + CN2 \quad (\text{Eqn. 7})$$

Where:

SACN2 = slope-adjusted CN for AMC II

CN2 = CN for AMC II

CN3 = CN for AMC III

α = soil slope (m/m)

Runoff calculation

Once the final CN values (adjusted for AMC and slope) are determined, runoff is calculated for each pixel using Eqn. 3. The steps are summarized in Fig. 1, representing flow from CN assignment to runoff estimation.

DSS interface and implementation

The web-based DSS was implemented using Google Earth Engine's JavaScript API to facilitate runoff estimation and prediction. The interface integrates multiple geospatial datasets and computational models within a single analytical framework.

Table 1. Geospatial datasets used for runoff estimation

Dataset	Source	Resolution	Purpose
Sentinel-2 LULC	ESA Copernicus (12)	10 m	Land-use classification
CMIP6 projections	NASA NEX-GDDP (13)	25 km	Projected rainfall
CHIRPS rainfall	UC Santa Barbara (14)	5 km	Historical precipitation
Digital Elevation Model (DEM)	NASA SRTM (15)	30 m	Topography
Soil texture	OpenLandMap/USDA (16)	250 m	Soil hydrological groups

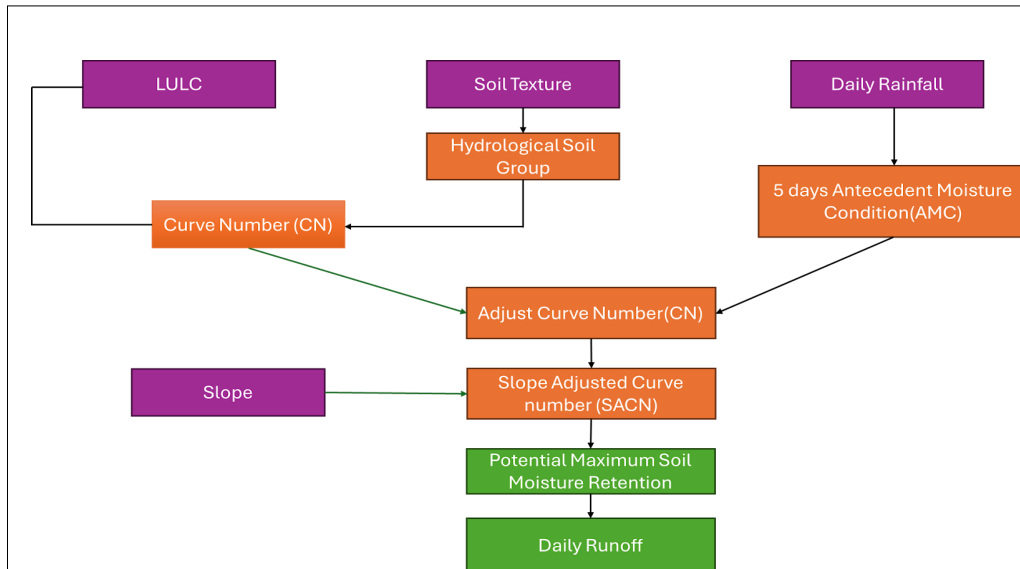


Fig. 1. Workflow of the modified soil conservation service curve number runoff estimation process incorporating slope-adjusted curve numbers and antecedent moisture conditions.

Interface architecture and user interaction

The DSS employs a client-server architecture. The client interface handles user input (e.g., specifying an area of interest via polygon drawing and specifying a temporal range) and visualization. Fig. 2 illustrates the interface layout, including the geospatial map panel, parameter input (e.g., date ranges, future projections option) and analysis execution button. The user interface design prioritizes core analytical functionality while maintaining ease of use through standardized Geographic Information System (GIS) interaction patterns, ensuring a minimal learning curve.

Server-side processing (Google Earth Engine)

Server-side layers, which are stored in Google Earth Engine (GEE), handle and process the data, as shown in Fig. 3. The data integration layer integrates major geospatial data sets: Sentinel-2 imagery (for LULC), OpenLand soil data, SRTM topography data and precipitation data sets (CHIRPS for historical, CMIP6 for future) into an integrated computational environment. The Processing Layer executes the modified SCS-CN algorithm,

applying the necessary AMC and slope correction adjustments as described in the methodology. Subsequently, the output generation layer produces the final outputs, including spatial runoff maps, time-series data, historical runoff estimates, future projections (if selected) and options for exporting results.

Decision Support System implementation leverages GEE's powerful parallel processing capabilities, ensuring computational efficiency. This enables quick analysis even in large watersheds without requiring significant local computing resources from the user. Its web-based platform eliminates the need for complex software installation, enabling easy access via standard web browsers (e.g., Google Chrome, Firefox, Edge) for advanced hydrological modelling capabilities. Furthermore, parameter-driven analysis using standardized datasets within the GEE environment promotes reproducibility, ensuring consistent results across users and study areas. This implementation approach delivers robust, efficient runoff estimation capabilities while remaining accessible to stakeholders with varying levels of hydrological modeling expertise.

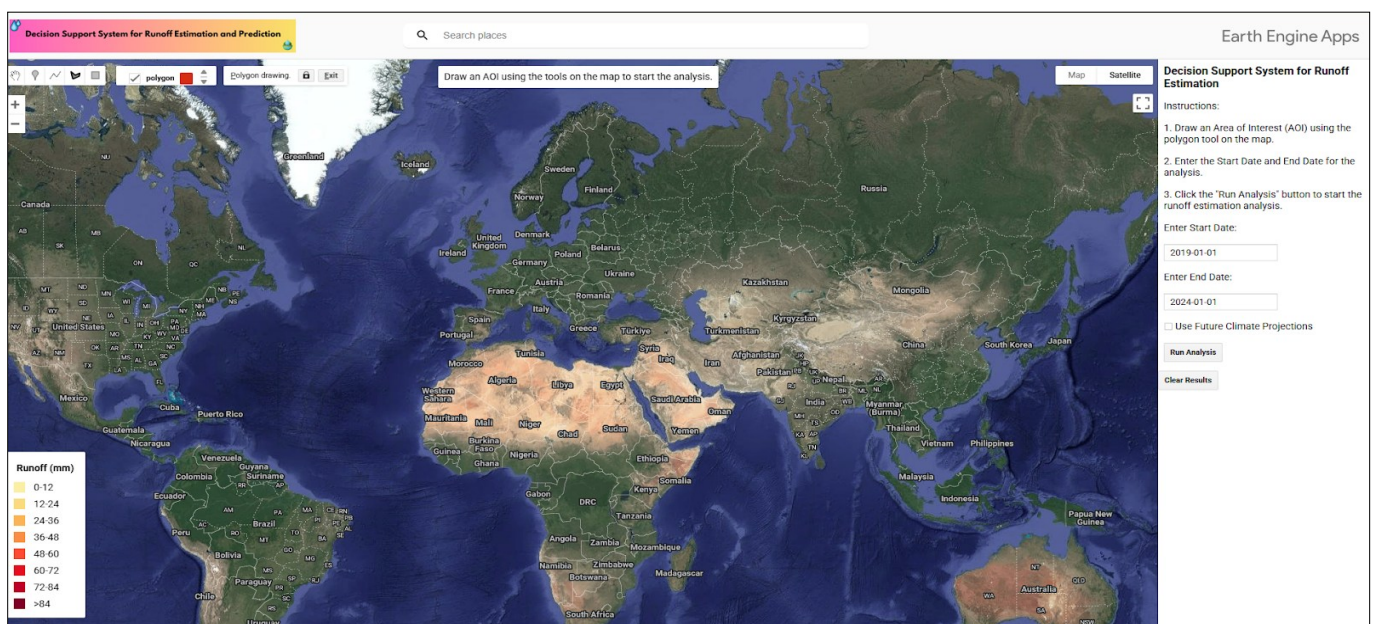


Fig. 2. Web interface of the cloud-based decision support system showing interactive runoff analysis tools.

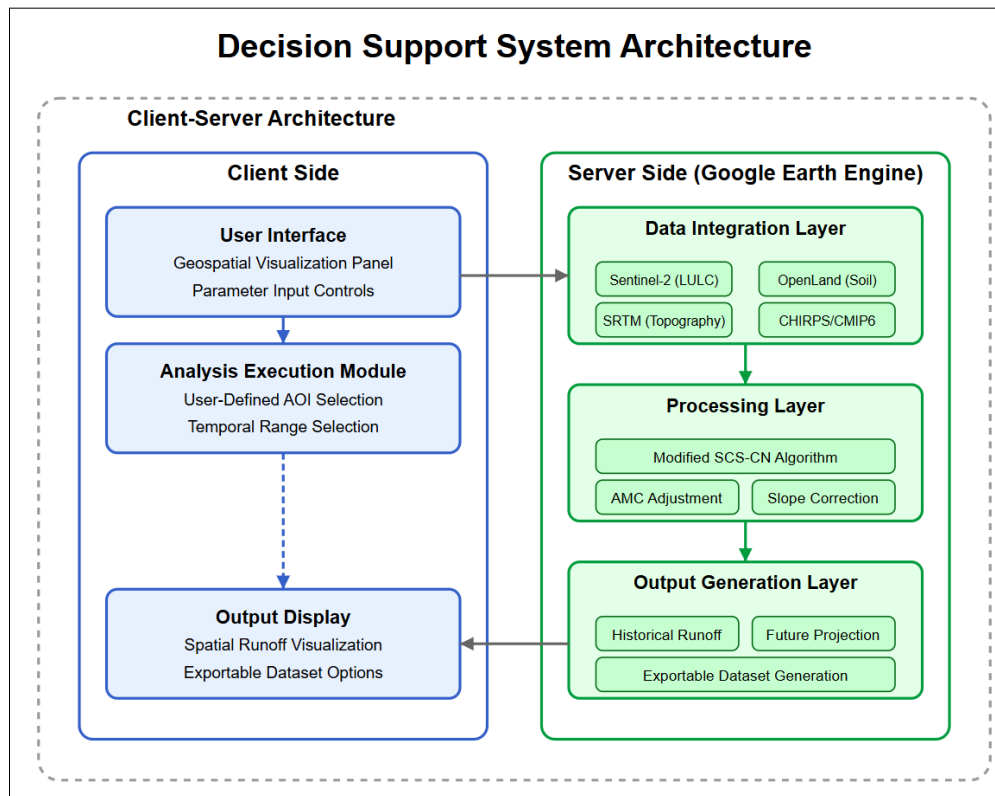


Fig. 3. System architecture of the Google Earth Engine-based decision support system.

Results and Discussion

The DSS was validated across highly contrasting Indian hydrological environments: the large, monsoon-dominated Salebhata catchment (4589 km²) and the small, semi-arid Venkatapur sub-watershed (685 km²). Observed runoff data for these sites were obtained from the Central Water Commission (CWC) offices in Bhubaneswar and Bengaluru, respectively. Strong agreement between simulated and observed runoff was achieved in both regimes ($R^2 = 0.82$ and 0.78 , respectively) (Fig. 4a, b & 5a, b), affirming the DSS's robustness across divergent climatic regimes and spatial scales. This robust validation in varied environments underscores the potential for broader applicability. DSS accurately captured critical hydrological signatures characteristic of these distinct regimes. In the Salebhata catchment, it effectively simulated intense monsoon-

driven runoff peaks and seasonal runoff volumes, demonstrating its utility for flood forecasting in similar high-rainfall, seasonally dominated basins globally. Conversely, in the Venkatapur watershed, the system successfully replicated a complex bimodal runoff pattern typical of semi-arid climates with distinct rainy periods, providing crucial runoff intelligence to inform water-harvesting planning and resource management strategies in water-scarce regions worldwide. This validated adaptability stems from the DSS's core architecture on the GEE platform, which integrates high-resolution, globally available geospatial inputs (Sentinel-2 LULC, SRTM topography) with advanced soil data and distinct precipitation datasets (CHIRPS) for near-real-time analysis and future climate projections (CMIP6). This enables the model to effectively represent local landscape controls on runoff (19), such as complex terrain and

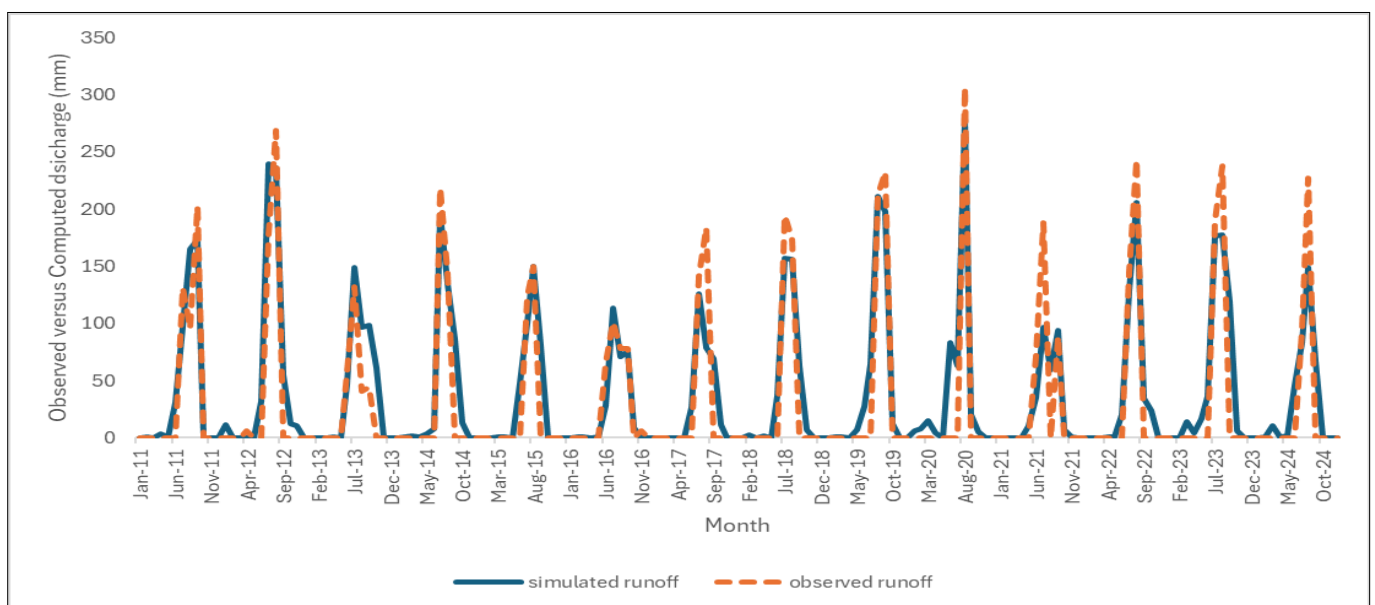


Fig. 4a. Monthly observed versus computed runoff time series at the Salebhata catchment.

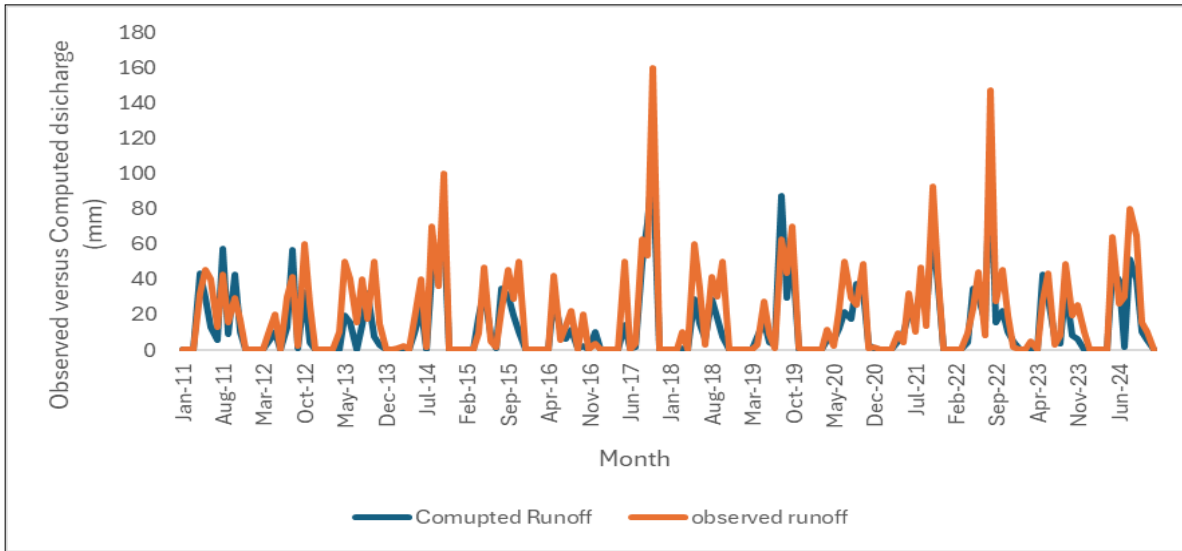


Fig. 4b. Monthly observed versus computed runoff time series at Venkatapur sub-watershed.

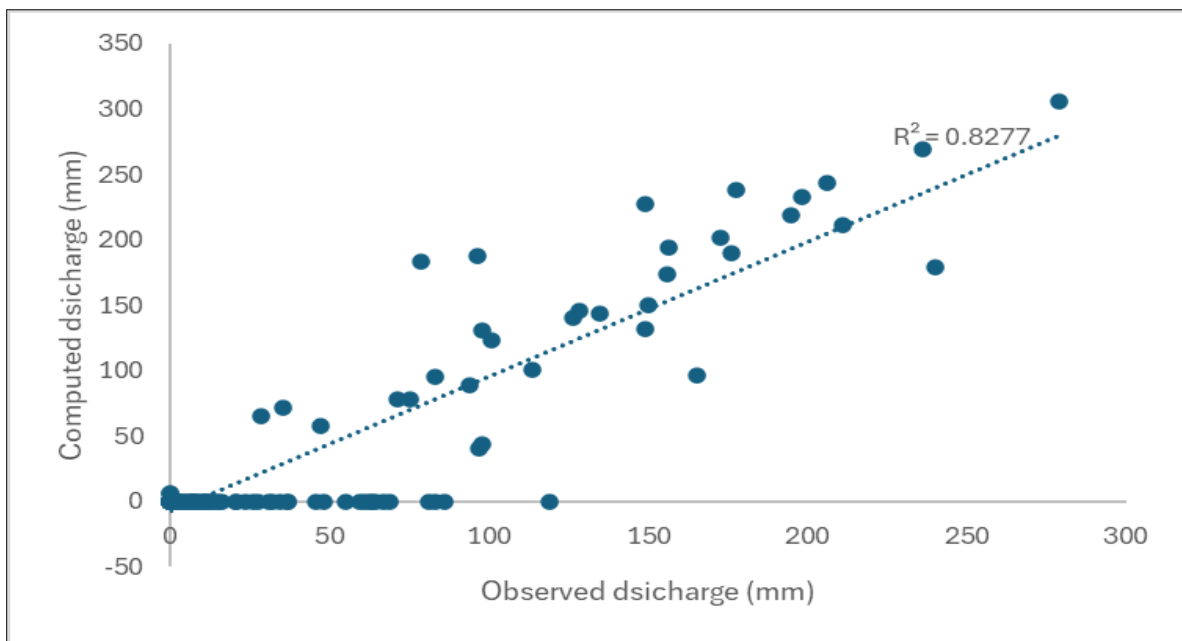


Fig. 5a. Scatter plot for observed versus computed monthly runoff at the Salebhata catchment.

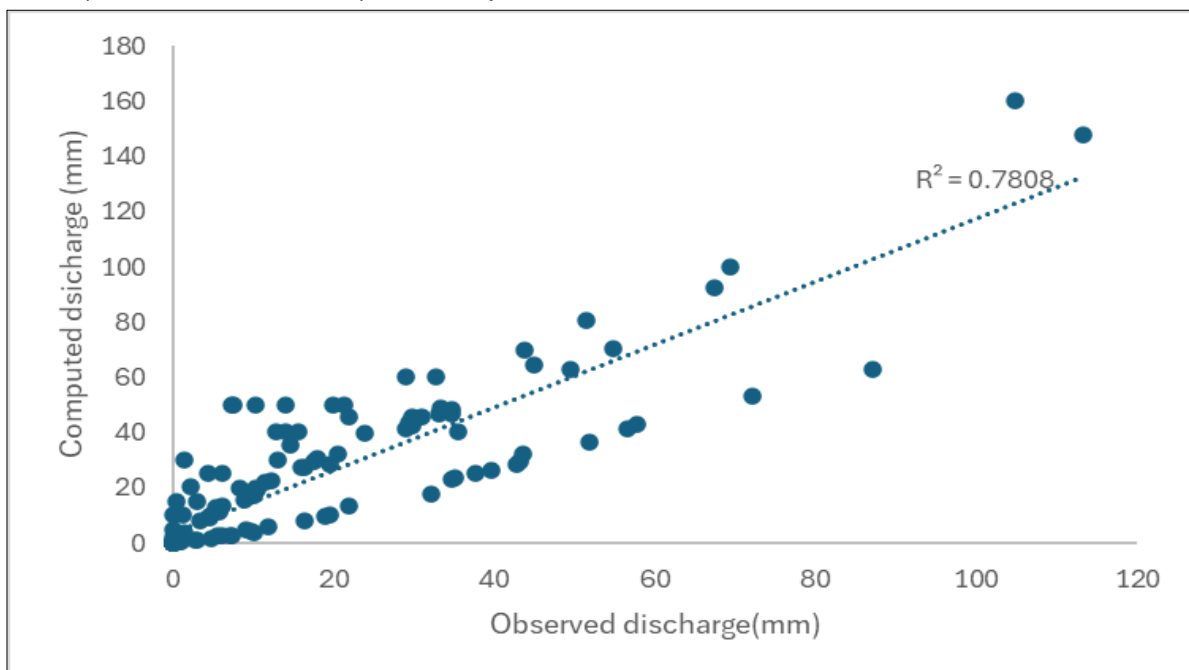


Fig. 5b. Scatter plot for observed versus computed monthly runoff at Venkatapur sub-watershed.

specific soil hydrological responses (e.g., vertisols), while also adeptly capturing transitions between wet and dry conditions driven by diverse climatic cycles. Furthermore, the DSS framework readily incorporates climate projection datasets (CMIP6), facilitating assessments of future water resource scenarios crucial for proactive, long-term, climate-resilient planning (20). The system's proven scalability, demonstrated across micro-watersheds to large catchments, confirms its versatility. Consequently, this work delivers a powerful, replicable and scalable DSS, has the potential to significantly enhance flood resilience, optimize water allocation and support sustainable water management globally (21). Its utility is particularly pronounced for regions lacking dense ground-based monitoring networks yet facing significant hydroclimatic pressures.

Conclusion

This study advances runoff modeling through a cloud-based DSS. The DSS integrates a Soil SCS-CN method, refined through slope adjustments and leverages Sentinel-2 imagery alongside other geospatial data. Validated in contrasting Indian watersheds the monsoon-dominated Salebhata and the semi-arid Venkatapur the system delivers high accuracy in terms of simulating seasonal runoff response and hydrologic extremes. This ability underpins enhanced flood prediction and supports effective water resource planning. The open GEE architecture fully addresses hydrological heterogeneity in space and time, providing policy-makers with a useful tool for advancing SDG-aligned water management. Future development plans include integrating Internet of Things (IoT) data to provide dynamic AMC updates and using machine learning to further enhance prediction accuracy and enable worldwide application.

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Authors' contributions

DO and SS participated in conceptualization and wrote the original draft of the paper. SS supervised, composed and carried out the review part. PS, RM, RK and RV reviewed the contents and edited the manuscript. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

Ethical issues: None

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