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Hydrological Model-Based Planning of Soil and Water Conservation Practices for Enhanced Watershed Saturation and Sustainable Development in a Semi-Arid Region

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ABSTRACT

The strategic use of Soil and Water Conservation (SWC) techniques is essential for efficient watershed management and hydrological processes in semi-arid areas. This study elaborates on a scientific framework following a ridge-to-valley approach for model-based planning of land and drainage line treatments to develop a stage of the watershed known as watershed saturation, where the maximum generated runoff is conserved while maintaining environmental flow downstream. Using the Soil and Water Assessment Tool (SWAT), the study modelled the hydrologic processes in the Chikkodi sub-watershed, a semi-arid region. The assessment of existing SWC measures (bunding, trenching, Checkdam, etc.) formed a key baseline analysis; it revealed a significant 26.17% runoff reduction due to the combined effect of existing SWCs and provided insights for subsequent planning. Based on the model outputs, this study recommends land treatment, that is, bunding and trenching, in the identified critical areas, which effectively intercept the runoff at the source and maximize infiltration. Conservation of the remaining runoff through drainage line treatments (check dams) is proposed as the next crucial step in the ridge-to-valley strategy. This study highlights the necessity of a science-based framework for the sustainable management of semi-arid watersheds, emphasizing that with improved watershed saturation, there is increased local water availability, which supports environmental flow. By combining the assessment of existing treatments with hydrological modeling for proactive planning, the proposed methodology provides a flexible and transferable approach to SWC practice optimization for enhancing watershed water storage in similar semi-arid landscapes.

INTRODUCTION

Water and soil are the most precious resources on the Earth's surface, which contribute to building a balanced ecosystem and promoting sustainable security of life (Hunt 2005, Pande et al. 2020, Rashmi et al. 2022). Watershed management is the process of planning and directing the use of soil, water, and other natural resources within a watershed to provide necessary products and services while minimizing impacts (Singh et al. 2014, Smyle et al. 2014, Surya et al. 2020, Santos et al. 2023). In a growing nation like India, Soil and Water Conservation (SWC) measures, such as bunding, trenching, contour farming, and check dams, are essential for sustainable resource management that balances the environment by promoting water conservation, regulating surface flow, and preventing soil erosion (Bhandari et al. 2007, Kumawat et al. 2021, Dharmawan et al. 2023).

While research highlights the complementary local influence of SWC methods, their impact at the watershed scale requires comprehensive evaluation to guide effective management plans. However, studies quantifying watershed-level impacts are limited. Field experiment data cannot be extrapolated to the watershed scale and must be tested with mathematical models to assess SWC effectiveness (Raza et al. 2021). Hydrological approaches can be used to examine the performance of soil and water conservation practices in mitigating or triggering adverse environmental effects. Hydrological modeling is the most commonly used approach for analyzing the effects of conservation measures on hydrological processes (Liu et al. 2017). Physically based hydrological models, which account for the spatial and temporal distributions of land use, topography, soil, and management practices, are particularly well suited for evaluating the impacts of different factors on watershed hydrology (Devia et al. 2015). Popularly used physically based rainfall-runoff models include MIKE-SHE, HEC-HMS, APEX, and SWAT (Nesru 2023).

Studies of the SWAT model have demonstrated that it is reliable for hydrological analysis. Thus, among several mathematical models, SWAT was chosen to evaluate the impact of SWC measures on watersheds. SWAT is data-intensive, requiring extensive spatial and temporal data (Uniyal et al. 2020), and provides continuous simulation over long periods. Numerous studies have successfully used SWAT at the watershed scale to examine the impact of SWC measures on land and water quality (Naseri et al. 2021, Singh et al. 2023). The water balance component derived from the SWAT model supports water budgeting for hydrological assessment and also forecasts water demand for various purposes, such as domestic and agricultural (Bandi & Patil 2022). Su et al. (2023) used the SWAT model to assess the influence of constructing water conservation projects on runoff from the mountain in different seasons and reported that the model has good applicability in the study area for runoff assessment. Strategic planning and agricultural growth can benefit from the SWAT model's ability to forecast future water availability (Verrma et al. 2022). Therefore, using the hydrological model SWAT is the best way to assess how adopted SWC interventions have affected hydrological processes (Sharma et al. 2024), thus confirming this approach for the present study to assess the impacts of SWCs and the hydrological stage of the watershed relevant to treatment.

In the context of this study, watershed saturation is achieved through the optimal placement and implementation of SWCs. This stage represents the highest retention of the generated runoff in the boundaries of the watershed, while providing for ecological balance, and a desirable amount of runoff called environmental flow, to be allowed to flow downstream beyond the watershed boundary.

Achieving watershed saturation, which inherently includes maintaining minimum flow regimes, is critical for ecosystem conservation downstream, underscoring the importance of environmental flows (Zeiger & Hubbart 2018). Environmental flows refer to the specific amounts, qualities, and timing of water flows necessary to maintain the viability of freshwater and estuarine ecosystems and the livelihoods that depend on them (Yarnell et al. 2020, Hoque et al. 2022). The impact of SWC implementation on environmental flows can be assessed by changes in average annual flow and flash flood frequency after implementation (Mawasha & Britz 2022), which is important for developing a sustainable ecosystem through the implementation of BMPs (Naganur et al. 2024).

The subwatershed (4D7E5) of Chikkodi Taluk, Belagavi District, Karnataka, provides a compelling case study. Before 2012, it suffered significantly from increased soil erosion and heavy runoff. The Government of India's Integrated Watershed Management Program (IWMP), introduced in 2009-10, aimed to restore ecological balance by conserving and developing degraded natural resources (Singh et al. 2010). SWCs were adopted for Project IWMP 19/11-12 in the study area (4D7E5); however, even with these interventions, a comprehensive study has not been conducted to assess their impact on improving the health of the watershed, its water retention capacity, or on attaining the desired condition of saturation. Therefore, a rigorous evaluation of the effects of these existing SWCs on the hydrology of the subwatershed was necessary as a baseline. Subsequently, to achieve optimum runoff conservation and effectively plan SWCs to move toward watershed saturation, a science-based approach that considers existing treatments is essential for sustainable watershed development.

Although many studies have investigated SWC at the local scale, its implications at the watershed level, particularly in achieving a managed state of watershed saturation through integrated planning, are poorly understood. Quantitatively, this methodology differs from past SWC planning studies in India that use SWAT models, primarily by clearly defining the planning objective, that is, retaining 70% of the generated runoff (excluding environmental flow) in the watershed while maintaining the necessary environmental flow downstream (Development of DSS under SUJALA III Project 2019). To deliver evidence-based refinement, this framework is based on a comprehensive baseline evaluation of existing IWMP-based impacts. Criteria are then iteratively formulated using the Sujala-III Decision Support System (DSS) to provide targeted, site-specific prescriptions. For example, in catchments with a runoff of at least 850 m3, check dams should be given priority in new SWC. The related recommendations provide specific quantitative thresholds of watershed saturation, among others, and siting and design specifications for the most significant SWC components, thus supporting the conversion of planning into practice.

The scientific novelty of this study lies in its unified, science-based approach. This approach integrates authentic field data on geotagged SWCs from the IWMP-19/11-12 project with a calibrated and validated SWAT model. The model supports both a comprehensive assessment of the existing IWMP SWCs and the formulation of a ridge-to-valley SWC plan guided by the scientific criteria developed by the authorities. This framework specifically targets watershed saturation while optimizing runoff conservation and maintaining environmental flow, representing a novel contribution to the discipline. By integrating these components, this study provides a robust framework for SWC planning aimed at achieving watershed saturation through effective runoff conservation using hydrological modeling.

MATERIALS AND METHODS

Study Area

This study was conducted in the Chikkodi watershed (52.77 km^2) of the middle Krishna Basin in southern India. It is located between 74°23′51″ and 74°28′55″ E longitude and 16°22′4″ to 16°29′38″ N latitude (Fig. 1). Local People's livelihoods in the area are dependent on dryland agriculture, which is susceptible to irregularities in nature. An " agro-climatic zone" is a geographical unit based on climates that are suited for a certain set of crops and cultivars. There are 15 agro-climatic zones in India, where Karnataka lies in zone 10 of the agro-climatic region, and the Chikkodi watershed of Belagavi district of Karnataka state comes under the

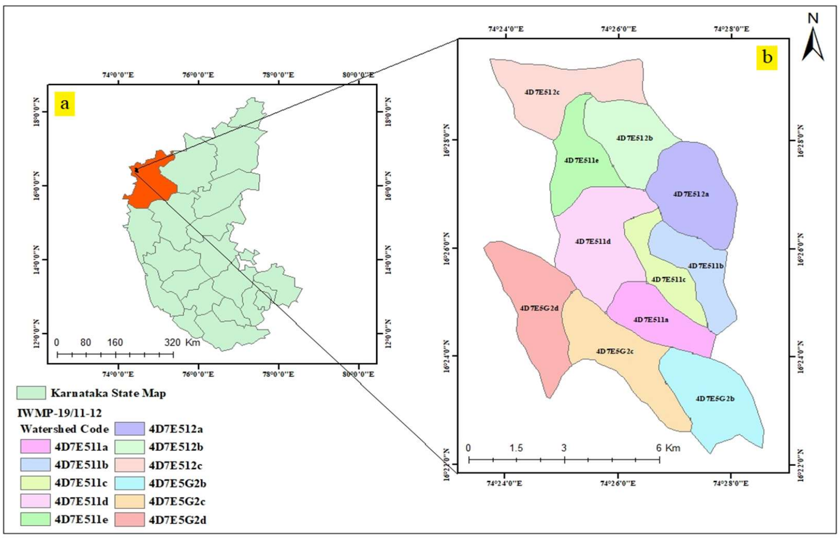

Fig. 1: Study area hierarchy. (a) Location within Karnataka, India (inset). (b) Detailed subwatershed distribution and codes.

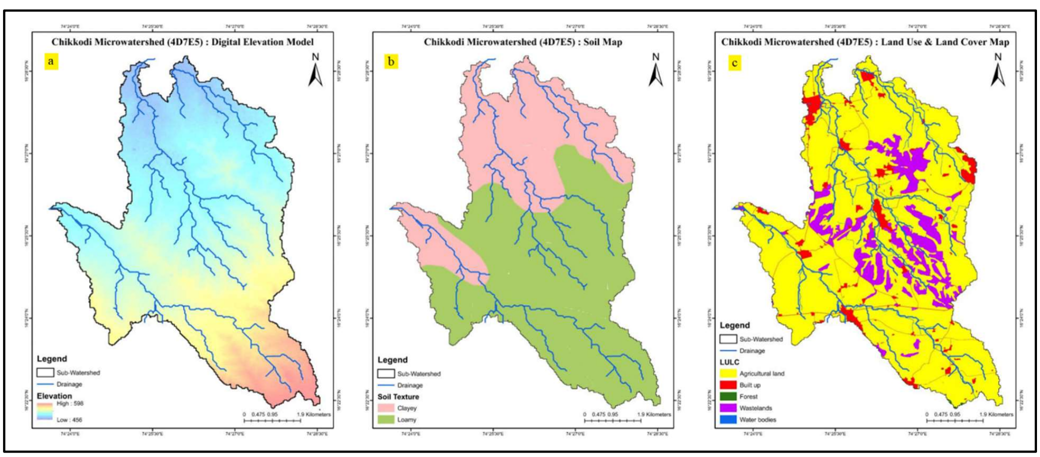

Fig. 2: Hydrological modeling input maps for the Chikkodi subwatershed (4D7E5): (a) Digital Elevation Model (DEM), (b) Soil Map (texture), and (c) Land Use and Land Cover (LULC).

Northern Transition Zone. The annual rainfall in the region is approximately 663 mm. The climate of the research area is semi-arid (CGWB 2017). The highest temperature ranges from 27°C to 35.7°C, whereas the minimum temperature ranges from 13.9°C to 20.6°C (CGWB 2012). The study region includes both flat and steep terrains (Honnannanavar et al. 2023). Fig. 2(b and c) depicts the soil and land use maps, which illustrate that agriculture accounts for the vast majority of land use.

The main streams that run through the study region are heavily silted and lack water-collecting devices, although they are connected to numerous secondary and tertiary streams. During the rainy season, stream flow may be observed. The flow period may vary from June to September (Honnannanavar et al. 2023). The major portion of runoff from the watershed ends as muddy water in the Krishna River. The area is reported to have excessive runoff during peak rainfall events, causing soil erosion and sediment transport, and hence an urgent need for watershed management approaches to improve rural livelihoods by improving agricultural production and water availability for a longer period.

SWC Measures Implemented in the 4D7E5 Microwatershed

SWCs function as sustainable instruments that promote water preservation, control water flow at the surface and below, and minimize soil erosion, thereby advancing sustainable resource management (Yan et al. 2023). Soil losses across the 4D7E5 watershed measure between 900-1100 $Mg.km^{-2}.y^{-1}$ from sheet, gully, and rill erosion activities (IWMP-19/11-12). Numerous SWCs, including contour bunds, trench cum bunds, check dams, and nala bunds, were installed in the subwatershed.

Farmland bunds serve as an effective method to stop surface runoff, but this runoff management action harms crops if not adopted scientifically. Bunds create multiple benefits because they allow more water to penetrate the soil layers. Agricultural yield productivity improves by 15 to 20% when contour bunds that run parallel to elevation lines are used (Madegowda et al. 2021). Such bunds function best in areas that experience rainfall below 800 mm per year with porous soil foundations. The study region receives adequate rainfall (663 mm) annually on its exclusively agricultural land, where clay-loam soil predominates, making contour bunds a suitable practice. Check dams function as structural SWC elements constructed using stones to decrease rainwater runoff and support soil infiltration, providing water for irrigation to nearby agricultural fields. Every dimension of a check dam significantly enhances its ability to minimize rainwater overflows and capture sediments.

Under project IWMP-19/11-12, through watershed development by the Government of Karnataka, a treatable area of 46 km² received earthen field bunds and trench treatments according to project specifications. As part of the drainage line treatment, a series of check dams and Nala bunds were adopted. The geotagged locations of these SWCs were collected from authorities, and their spatial extents are shown in Fig. 4.

SWAT Model

SWAT is a watershed simulation model developed by the USDA Agricultural Research Service through the efforts of Dr. Jeff Arnold (SWAT Theoretical Document 2009). SWAT requires extensive data input from the study region because its methodology depends on numerous geographical and temporal variables (Uniyal et al. 2020). Notable inputs required for building the baseline model include digital elevation data, spatial data of land use and land cover and soils, meteorological precipitation and temperature data, slope information and stream flow, along with sediment data time series (Neitsch et al. 2011).

SWAT implements this water balance equation, which Nasiri et al. (2020) specified as:

$$SW_t = SW_0 + \sum_{i=1}^{t} R_{day} - Q_{surf} - E_a - W_{seep} - Q_{gw} \quad ...(1)$$

Where,

SW_t = final soil water content (mm)

SW_0= initial soil water content on ith day (mm)

R_{day} = daily precipitation on the ith day (mm)

E_a = evapotranspiration on the ith day (mm)

W_{seep} = amount of water percolating into the soil (mm)

Q_{gw} = amount of return flow (mm)

Input Data for the SWAT Model

A digital elevation model (DEM) with a spatial resolution of 30m is sufficient for performing hydrological simulations (Ayana et al. 2012). Land use data and soil data were obtained from https://swat.tamu.edu/ website (Indian dataset for SWAT 2012), Land Use Water base (worldwide data), and Soil HWSD FAO (worldwide data), respectively. Weather data comprising precipitation, temperature, solar radiation, wind speed, and relative humidity were also obtained from the https://swat.tamu.edu/ website (Global dataset for SWAT 2012) for 20 years (2000-2020). Furthermore, the monthly streamflow for the year 2004-2020 for the Sadalga gauging station was acquired from the India Water Resource Information System (https://indiawris.gov.in/wris/#/RiverMonitoring).

Table 1: Performance parameter for the SWAT model (Moriasi et al. 2007).

Performance	NSE	R^2
Very Good	0.75 - 1	0.75 - 1
Good	0.65 - 0.75	0.65 - 0.75
Satisfactory	0.5 - 0.65	0.5 - 0.65
Unsatisfactory	≤ 0.5	≤ 0.5

During the initial soil water conditions balance, monthly model simulations were run for the three-year warm period of 2000–2003. Based on the availability of observed discharge at the basin outlet, the simulation period (2004–2020) was used as the baseline period. Consequently, the SWAT model was calibrated and verified for this time frame.

SWAT Model Performance Assessment

A performance measurement method calculates the model output rate variation when the input parameters experience variations (Moriasi et al. 2007). The evaluation process of the models directly depends on their performance assessment requirements. The model evaluation demonstrated how well the models performed in the historical reference period compared to the observed river flow and other factors (Najafzadeh & Anvari 2023). The model performance was evaluated by calibrating and validating the model findings against observable values.

Manual and auto-calibration and validation can be performed to assess the model performance. Tuppad et al. (2011) contend that manual calibration is preferable to automatic calibration. Manual calibration uses an iterative system that follows the sequence of running simulations, examining observed values against SWAT-calculated values, and modifying parameters within their relevant ranges based on the published literature until optimal correlations emerge. Model performance was evaluated using the coefficient of determination (R^2), Nash–Sutcliffe coefficient (Nash & Sutcliffe 1970), and percent bias (PBIAS) (Moriasi et al. 2012). Moriasi et. al. (2007) proposed that general performance parameters are given in Table 1.

The Chikkodi watershed underwent model calibration for runoff through manual and auto-calibration (SWAT-CUP) techniques over 20 years from 2000 to 2020 using a three-year warm-up phase from 2000 to 2003. Monthly streamflow information served as the basis for calibrating and validating the model. The model calibration spanned 7 years from 2004 to 2011, whereas the validation took place during the subsequent 9 years from 2011 to 2020. The proper parameters were adjusted until the model predictions for monthly stream flow matched the observed data at the watershed outlet locations.

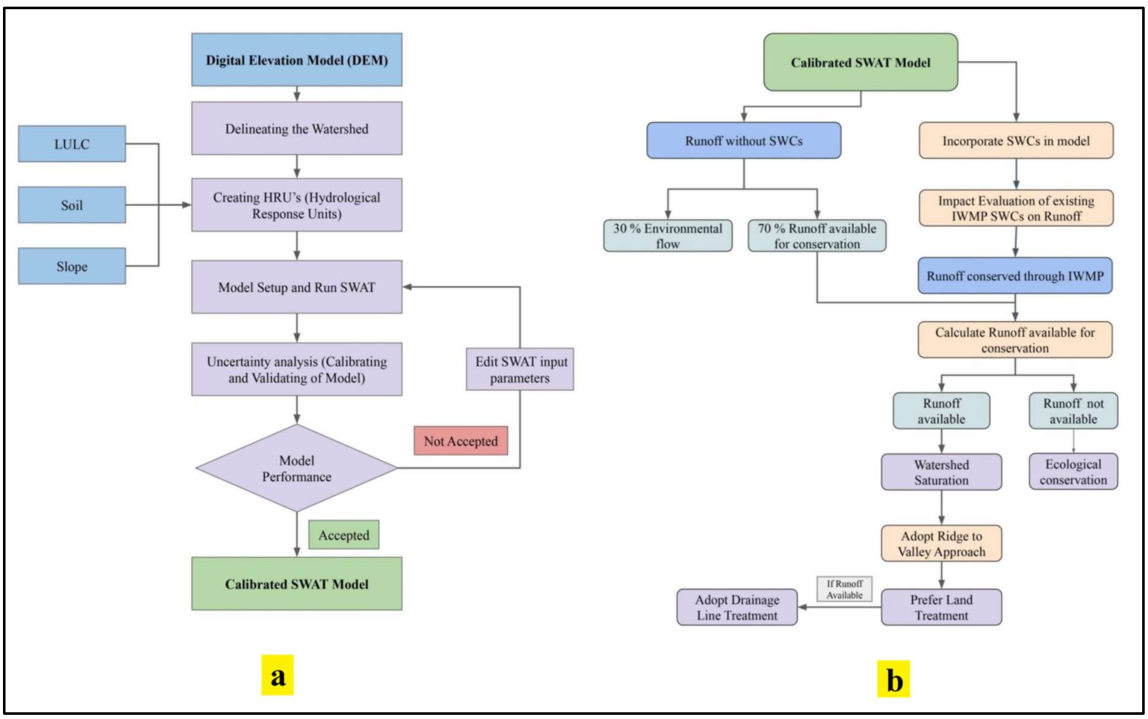

Fig. 3: Methodological flowchart for (a) SWAT model implementation and (b) Decision-making framework for watershed saturation using SWC measures derived from SWAT modeling.

Methodology

The flowchart (Fig. 3-a) demonstrates the progression from basic spatial layers, including the Digital Elevation Model, land use/land cover, soil, and slope, and then shows watershed processing and model simulation while integrating calibration and validation until the SWAT model is attuned. The flowchart describing the determination of SWC practice implementation (ridge-to-valley approach and drainage line treatment along with land treatment) through runoff assessment (SWC presence vs. absence) for calculating conservation potential using watershed saturation levels and available runoff is shown in Fig. 3-b.

Modeling SWC Impacts on Runoff in SWAT

The sustainable practice of SWC structures reduces soil loss due to soil erosion, with surface water flow regulation to improve water conservation in the environment. Sustainable resource management is possible because of SWC measures (Melaku et al. 2017). SWC structures have already been established in numerous micro-watersheds to control soil erosion. The lowered flow velocity and sediment deposition at the structure's crest serve as the main erosion reduction methods, preventing channel or gully formation on the downstream side (Nabi et al. 2020). SWC methods, such as contour bunding, trenching, and terracing, as well as structures such as check dams, farm ponds, and nala bunds, control soil erosion and enhance moisture retention, promoting agricultural development.

Table 2: SWAT parameters for SWC measures (Source: Uniyal et al. (2020)).

Type of SWC	SWAT parameters (input files)	Value of SWC in good condition
Contour bunding	SLSUBBSN (.hru)	$\frac{(0.1 * slope * 0.9) * 100}{slope}$
	CN2 (.mgt)	CN2 calibrated values were lowered by 6
	USLE_P (.mgt)	0.1, for slope 3 to 5% 0.12, for slope 6 to 8%
Trenching	SLSUBBSN (.hru)	10 m, for slope 10-20% 9.1 m for slope >20%
	USLE_P (.mgt)	0.32

The SWAT hydrological model enables users to model SWC systems using specified model parameters. The model simulations used parameter value changes based on Table 2 to simulate the SWC process. The research area has approximately 60 sub-basins where contour bunds have been implemented (Fig. 4). A SWAT-based runoff simulation was conducted by adjusting the suitable model parameters. Table 2 contains information about the SWC types, providing the

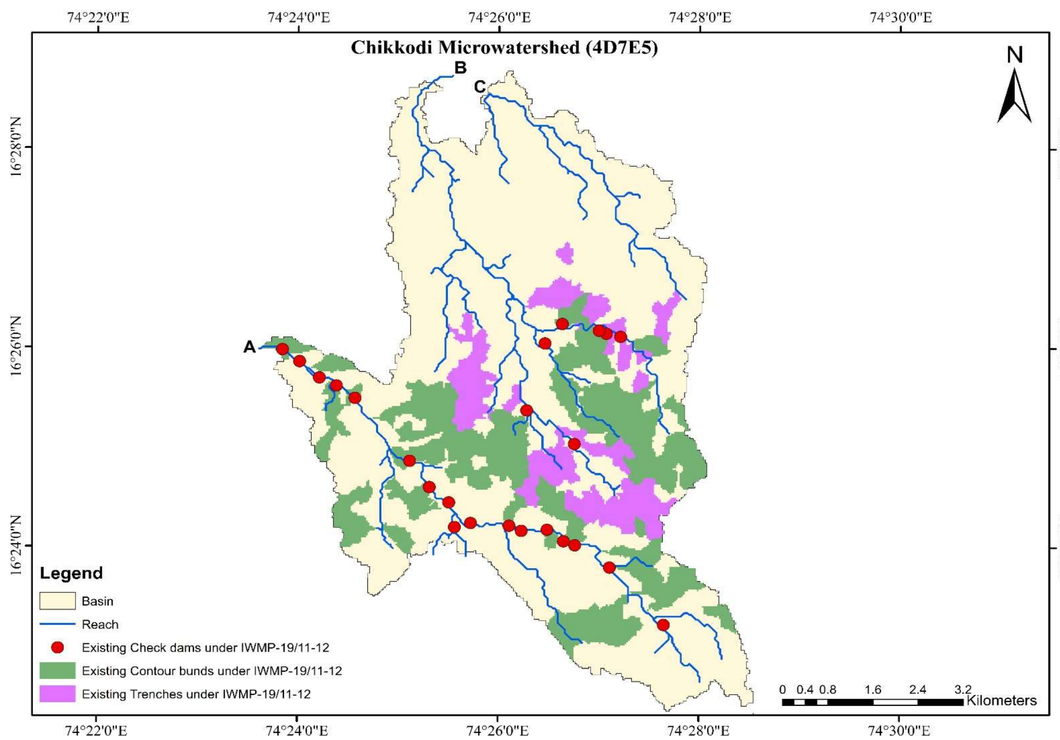

Fig. 4: Map of the Chikkodi subwatershed (4D7E5) showing the spatial extent of existing SWC infrastructure implemented through the IWMP (19/11-12).

SWAT input parameters used alongside the suggested values for good conditions and corresponding references.

A total of 21 check dams were implemented in the micro-watersheds to control the intense runoff impacts. The geotagged locations of the check dam were acquired from the IWMP program, as shown in Fig. 4. The construction of check dams was proposed at locations possessing stable embankments and soft-sloping stream beds while using durable geological layers beneath the drainage channel. The SWAT model represents check dams as conceptual ponds that require modification of PND_FR, PND_K, PND_PSA, and PND_VOL. By taking the height of the check dam as approximately 2.5 m, all other parameters were calculated and input into the SWAT model.

Using the formula outlined below, Uniyal et al. (2020) calculated the percentage decrease in runoff.

$$\textit{Runoff reduction} = \frac{\text{Model output without SWC} - \text{Model output with SWC}}{\text{Model output without SWC}} \times 100 \quad ...(5)$$

Runoff Conservation Strategies for Watershed Saturation

Areas that are highly exposed to hydrological extremes rely on watershed management for sustainable development. To minimize the impact of these extremes, SWC measures conserve excess runoff and reduce soil erosion. By considering a runoff conservation strategy, this study proposes a scientific method to achieve watershed saturation by adopting SWCs. This study offers a scientific approach to planning SWCs to achieve watershed saturation by conserving runoff.

Estimating Runoff with the SWAT Model

In the study watershed, the SWAT model was used to simulate runoff. The model's performance in simulating runoff was ensured by calibration and validation with observed data. Similarly, to understand the current hydrological regime, the impact of existing IWMP SWCs on runoff was assessed through runoff estimation using the SWAT model after implementing it into the model.

Strategic Runoff Allocation for Environmental Needs and Conservation

Ensuring environmental sustainability is an important component of this research. In a bid to make it ecologically sustainable, 30% of the original produced runoff was marked as environmental flow, while the remaining 70% was to be conserved. This allocation matches the country-wide recommendations of the Ministry of Environment, Forest & Climate Change (MoEF&CC), which has marked 30% environmental flow during the monsoon months in River Valley & Hydroelectric Projects (Ministry of Jal Shakti 2021). Since the context of our study region is semi-arid and dominated by monsoons, this practical division serves the objectives of conservation in addition to the maintenance of vital downstream flows. Hence, 30% of the initial runoff was allocated for environmental flow. Through SWC procedures, the remaining 70% of runoff was intended to be conserved. The efficiency of the existing IWMP SWCs in conserving runoff was calculated using the SWAT model. The remaining runoff was then considered for further conservation by deducting the runoff conserved through the IWMP SWCs from the total runoff.

A Ridge-to-Valley Approach for SWC Planning and Implementation

The ridge-to-valley strategy was used to plan further SWC measures. The objective of this strategy is to capture runoff and encourage infiltration at its source. Initially, except for the places where structures were already in place, the entire watershed was to be covered by bunding and trenching. The SWAT model was used to evaluate the impact of this scenario on runoff conservation. It was suggested to treat the drainage lines by building check dams to save the leftover runoff. After bunding and trenching, the positions of the check dams were established based on the distribution pattern of the runoff.

The success of field-level conservation efforts is critical to the long-term viability of the state's water and soil resources, especially those of large rainfed areas. The process of creating a conservation plan involves matching various conservation measures to the site-specific potentials and restrictions of the location and then selecting the most efficient option based on the available criteria. Rainfall quantity, landform, soil, land use, and other factors all play a role in determining the selection of treatment type. Bunding, terracing, and trenching are the main field-level treatments used for soil and water conservation.

Decision Support for Site-Specific SWC Planning

The primary purpose of the Decision Support System (DSS) is to facilitate the planning, execution, and oversight of watershed development initiatives within the state under the SUJALA-III project of the WDD, the Government of Karnataka, and other line departments in Karnataka. With this, authorities can develop a conservation map for any area by developing a DSS for SWC based on the criteria established in Table 3 (Development of DSS under SUJALA III Project 2019).

Table 3: Guidelines for selecting SWC treatments based on biophysical parameters, as defined by the Sujala-III DSS (Source: Watershed Development Department, Government of Karnataka 2024).

Sl. No.	Slope	Depth	Texture	Gravel	Rainfall (mm)	Treatment
1.	<1	<50	Loam	<35%	<750	Contour bunding/TCB
2.	1 to 3	<50	Loam	<35%	<750	Contour bunding/TCB
3.	3 to 5	<50	Loam	<35%	<750	Contour bunding/TCB
4.	<1	<50	Clay	<35%	<750	Graded bund
5.	<1	50 to 100	Clay	<35%	<750	Graded bund
6.	<1	>100	Clay	<35%	<750	Graded bund
7.	1 to 3	<50	Clay	<35%	<750	Graded bund
8.	1 to 3	50 to 100	Clay	<35%	<750	Graded bund
9.	1 to 3	>100	Clay	<35%	<750	Graded bund
10.	3 to 5	<50	Clay	<35%	<750	Graded bund
11.	3 to 5	50 to 100	Clay	<35%	<750	Graded bund
12.	3 to 5	>100	Clay	<35%	<750	Graded bund
13.	5 to 10	<50	Loam	<35%	<750	Graded bund
14.	5 to 10	<50	Clay	<35%	<750	Graded bund
15.	5 to 10	50-100	Loam	<35%	<750	Graded bund
16.	5 to 10	50 to 100	Clay	<35%	<750	Graded bund
17.	5 to 10	>100	Loam	<35%	<750	Graded bund
18.	5 to 10	>100	Clay	<35%	<750	Graded bund

Data Limitations and Uncertainties in the Model

The major sources of uncertainty related to hydrological modeling, especially in cases of SWC planning, are the quality and resolution of the input data. This study applied gridded precipitation and temperature records, the spatial resolution of which is insufficient to represent precipitation variations on a local scale, which will introduce uncertainty as runoff and water balance estimates are obtained. The 30m DEM is appropriate for analyzing the watershed, but it may not satisfactorily reveal finer topographic details that may influence the flow direction and delineation of critical areas where SWC interventions are carried out.

Moreover, the Land Use and the soil data to be used in the analysis have coarser scales because they are based on generalized global data, which may fail to reflect the complexity of land cover (and soil properties) found in the Chikkodi subwatershed. These simplifications may cause inaccuracies in evaluating important parameters of the SWAT model, such as CN values, soil water holding capacities, and hydraulic conductivities, causing uncertainties in determining the accuracy of the exact effects of SWC measures on local water balance components. Despite such inherent ambiguities in data, the best possible datasets were used

RESULTS AND DISCUSSION

In the present study, the SWAT model was used for the hydrological planning of SWC measures in the Chikkodi subwatershed, which experiences a semi-arid climate. Many studies on hydrological evaluation and water resource management in semi-arid regions have relied on the SWAT model for assessment, which is consistent with the approach followed in the current study. Rocha et al. (2023) comprehensively reviewed hydrological studies in semi-arid regions, particularly in Asian countries, which highlights the extensive and versatile applications of SWAT for hydrological and environmental management. In contrast, to assess hydrological responses under varying climate and land use, the SWAT model was adopted in Central Asia by Dolgorsuren et al. (2024) for guiding water resource management. For a semi-arid watershed in Turkey, Aibaidula et al. (2022) adopted the SWAT model to evaluate the climate change impacts on water availability. Sharma et al. (2023) quantified the SWAT's performance in a large semi-arid basin in assessing the Spatio-temporal pattern of water balance, which is geographically closer to the current study, providing firm and crucial insights relevant for the present study.

Streamflow Model Performance: Calibration and Validation

Calibration was performed for eight years, from 2004 to 2011, to match the simulated results with the observed data. The sensitive parameters were identified and adjusted to achieve better calibration. This was confirmed by the

Table 4: Identified sensitive parameters adjusted during the calibration and validation process.

Sl. No.	SWAT parameters	Minimum value	Maximum Value	Fitted Value
1.	CN2	35	98	82
2.	ALPHA_BF	0	1	1.04
3.	GW_DELAY	0	500	170.04
4.	SLSUBBSN	-29.67	91.67	3.69
5.	HRU_SLP	0.44	1.38	0.70
6.	ESCO	0	1	0.61
7.	EPCO	0	1	0.55
8.	SOL_AWC	-72.97	77.97	74.20
9.	SOL_K	0	2000	0.73

R^2 and NSE values between the observed and simulated results, which must be within the allowable limits. During the process, the sensitive parameters were adjusted to achieve maximum model efficiency, as shown in Table 4.

Although it is well acknowledged that measured data are fundamentally uncertain, model evaluation tends to neglect this uncertainty, possibly due to a lack of required data. Observations were taken at the Sadalga gauge station throughout the year from 2000 to 2020. A comparison and correlation analysis was established between the SWAT simulation results using seasonal runoff data for the mentioned year and the actual measured data. The procedure included both manual and autocalibration steps. The performance of the model for both manual and auto calibration is shown in Table 5.

Parameters that are essential in determining the effectiveness of the model, such as the NSE values, gave an initial result of 0.41, which indicates moderate performance in the manual calibrations. Nonetheless, to increase model accuracy and resilience, calibration and validation were further improved through auto-calibration by SWAT-CUP. This considerably enhanced the NSE values from 0.41 to 0.53 during calibration and from 0.65 to 0.72 during validation (Fig. 5).

Although the first manual calibration gave an NSE of 0.41, which had a limiting impact on being able to perfectly capture the observed variability as a 'Moderate', the subsequent auto-calibration controlled this. The resulting improved NSE values of 0.53 and 0.72 show that the model performance was rated as Satisfactory to Good, a level that is adequately acceptable for carrying out hydrological modeling in areas that are complex, data-deficient, or semi-arid in nature (Moriasi et. al. 2007). More importantly, for the planning of SWC based on relative changes and comparison of intervention effectiveness to reach the level of watershed saturation, this improved model performance of simulating overall hydrological responses is a solid source of strategic decision-making.

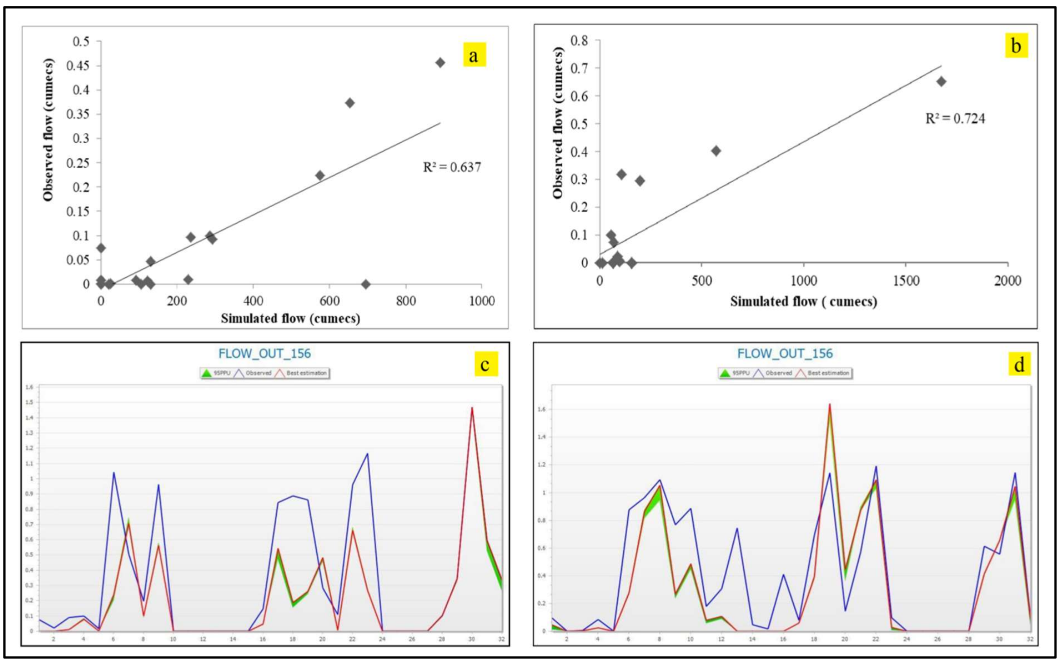

Fig. 5: Evaluation of SWAT model performance for stream flow simulation (a) Manual Calibration scatter plot, (b) Manual Validation scatter plot, (c) Auto-calibration hydrograph with 95% PPU, (d) Auto-validation hydrograph with 95% PPU. Calibration periods (2004-2011) and validation period (2012-2020).

Table 5: Runoff model fit statistics from manual calibration and validation.

Method	Calibration				Validation			
	R^2		NSE		R^2		NSE	
	Value	Performance	Value	Performance	Value	Performance	Value	Performance
Manual	0.63	Satisfactory	0.41	Moderate	0.72	Good	0.65	Satisfactory
Auto (SWAT-CUP)	0.62	Satisfactory	0.53	Satisfactory	0.77	Very Good	0.72	Good

Hydrological Impacts of Implemented SWC Measures

The spatial variation in the annual average runoff without any treatment in the watershed is shown in Fig. 6-b. In this scenario, spatially concentrated runoff was observed at outlets A and B. In the absence of water conservation treatment, all runoff generated within the watershed flowed out of the watershed with sediments. In this context, there was scope to conserve runoff by adopting various SWCs within the watershed.

Impact of Contour Bunds on Runoff

In the research region, contour bunds have been used in approximately 60 sub-basins. The effect of these contour bunds on simulating runoff was assessed by altering the appropriate SWAT parameters, as outlined in Table 2. According to the analysis conclusions, the implementation of this specific SWC solution had an acceptable impact, as the contour bunds decreased runoff by 7.03 %. The reduction in runoff has been shown in Fig. 6– c and Table 5.

The significant change in runoff concentration can be observed at outlet A when compared with Fig. 6- b, as the majority of bunds adopted in the watershed were situated in the catchment of drainage with outlet A. Minor variation is observed at outlet B, as less area was adopted under bunding

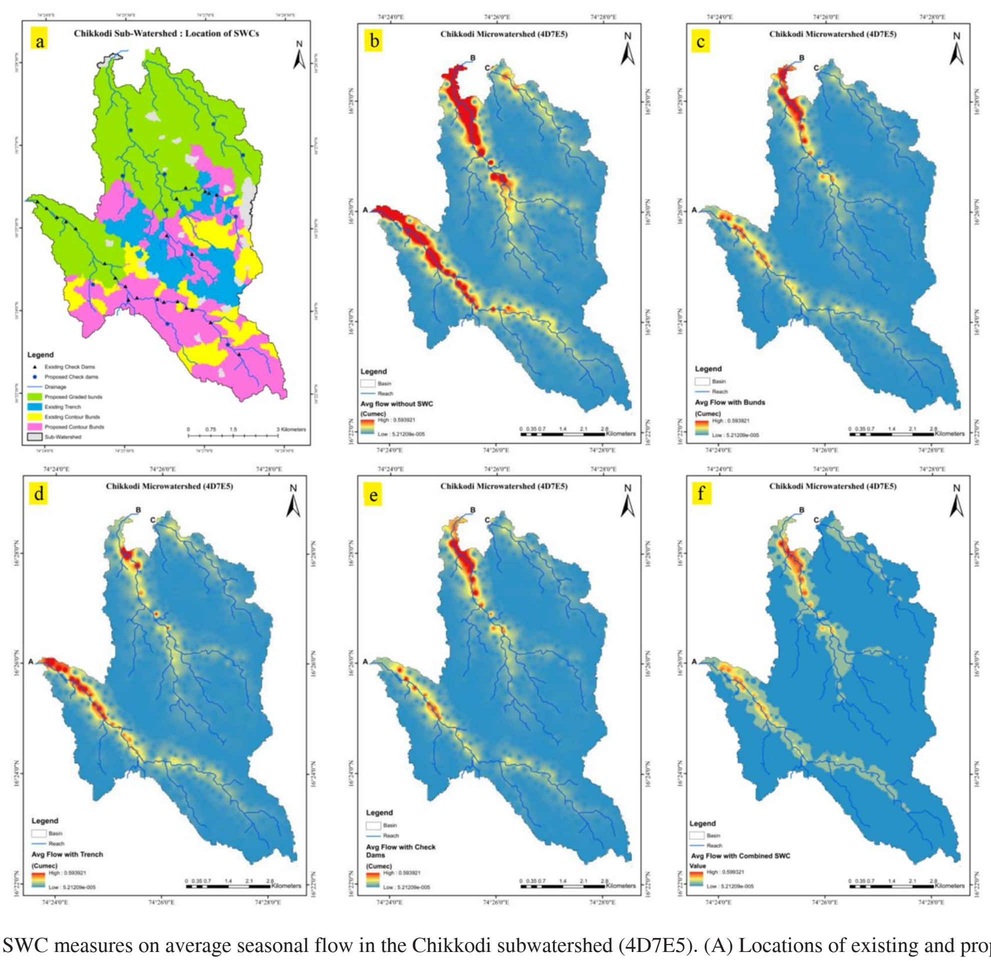

Fig. 6: Impact of SWC measures on average seasonal flow in the Chikkodi subwatershed (4D7E5). (A) Locations of existing and proposed SWCs. (B) Average seasonal flow without SWCs. (C) Average seasonal flow with bunds. (D) Average seasonal flow with trenches.

Table 6: Model-simulated runoff reduction (%) resulting from different SWC scenarios.

Scenarios	Description	Runoff reduction
Scenario 1	Contour bunds	7.03%
Scenario 2	Trenches	6.33%
Scenario 3	Check dams	18.08%
Scenario 4	Combination of all SWCs	26.17%

treatment. This spatial variation in the simulated runoff reduction demonstrates that the SWAT model effectively captured the localized impact of contour bunding within the watershed.

Impact of Trenches on Runoff

This study assessed the effects of trench installation on runoff simulation. According to Table 2, the HRU, parameter SLSUBBSN, and mgt were. (management) The USLE P parameter was changed. The SLSUBBSN was adjusted to 10m for slopes between 10% and 20% and 9.1m for slopes greater than 20%. According to the model simulation findings, trenches decreased runoff by 6.33 %. This demonstrates that trench installation has a better effect on runoff. Fig. 6-d and Table 5 illustrate the decreased runoff. A significant change in runoff concentration can be observed at outlet B when compared with Fig. 6-b, as the majority of trenches adopted in the watershed were situated in the catchment of drainage with outlet B. Negligible variation was observed at outlet A, as trenches were not adopted in that area.

Impact of Check Dams on Runoff

Approximately 21 sub-basin check dams have been adopted (Fig. 4) to reduce the vigorous impact of excess runoff at the research location, as per IWMP-19/11-12. SWAT has a conceptual visualization of the pond as a check dam; therefore, pond parameters such as PND_FR, PND_K, PND_PSA, and PND_VOL have been altered. By taking the height of the check dam as approximately 2.5 m remaining all other parameters have been calculated and input into the SWAT model. According to model simulation, results depict that the adoption of check dams has reduced the runoff by 18.08% reflected in Fig. 6- e and Table 5, which is comparable to the results of Xu et al. (2013).

A significant change in runoff concentration can be observed at outlet A when compared with Fig. 6 - a, as the majority of check dams were adopted on the drainage with outlet B. Minor variation was observed at outlet A in comparison with outlet B, as only a few check dams were placed on drainage B. This indicates that check dams are quite helpful in conserving significant amounts of runoff.

Combined Impact of SWCs on Runoff

The subsequent simulation was carried out to analyse the collective runoff conservation performance of SWCs applied together. The model considered the entire range of SWC measures that local authorities implemented across the watershed under the IWMP program. This integrated modeling aimed to assess the collective runoff reduction that occurs through distributed SWC implementation across the microwatershed. As demonstrated in this simulation, the cumulative impact of all implemented SWCs results in a significant 26.17% reduction in runoff, as depicted in Table 6 and Fig. 6-f. This result shows that the SWAT model can predict the cumulative hydrologic impacts of multiple SWCPs deployed within a watershed. The ability of the model to replicate the integrated effects is important when it comes to evaluating the overall impact of watershed development measures and forms a significant part of spatial strategies in conservation endeavors.

The reduction of 26.17% in the annual surface runoff measured at the outlet of the final subbasin is a direct and measurable outcome of the management practices (bunds, trenches, and check dams) carried out. This remarkable decrease is mainly due to the increase in the infiltration ability of the watershed, which is indicated by the reduction of the mean Curve Number from 81.99 to 81.45 (Table 7). Water that no longer becomes surface runoff is essentially redirected within the hydrological cycle, resulting in augmented actual evapotranspiration, improved recharge to shallow and deep aquifers, and changed subsurface hydrology, such as increased lateral and return flow, along with more evaporative loss of the shallow aquifer (revap). The combination of these changes shows that the management practices are successful in decreasing the flashy nature of the surface runoff and increasing water retention and groundwater recharging in the watershed.

Table 7: Average annual hydrological parameters (obtained from SWAT Checker) before and after the application of management practices.

Water balance component	Before SWC	After SWC
Precipitation	662.6	662.6
Surface runoff	85.59	82.9
ET	547.1	548.3
Percolation to shallow aquifer	28.32	29.72
Lateral flow	0.18	0.24
return flow	0	0.51
Revap from shallow aquifer	20.47	21.12
Recharge to deep aquifer	1.42	1.49
Average CN	81.99	81.45

Planning of SWCs to Achieve Watershed Saturation by Runoff Conservation

This study focused on planning SWCs for watershed saturation through runoff conservation. The impact of existing IWMP SWCs on runoff was assessed using the SWAT model to understand the existing hydrological regime. By designating 30% of the initial runoff as environmental flow, the remaining 70% was targeted for conservation through SWC measures. The effectiveness of the existing IWMP SWCs in conserving runoff was evaluated using the SWAT model, with the remaining runoff after accounting for these structures representing the available runoff for further conservation. The following criteria were used to propose the SWC in the watershed:

A ridge-to-valley approach was adopted for planning additional SWCs, focusing on capturing runoff at its source and promoting infiltration into the soil. By assuming the impact of existing IWMP structures, the correlation of the same structures was proposed in this study to conserve the remaining runoff from the available runoff after IWMP treatment. As per the ridge-to-valley approach, preference was given to land treatment, such as bunding and trenching, to avoid the degradation of land, which further causes silting in water bodies. After complete land treatment, the remaining runoff will be conserved by structures adopted in the drainage line treatment, preferably check dams. This approach results in watershed saturation. In this study, the same treatment was proposed to achieve watershed saturation by maintaining environmental flow. Table 8 presents calculations that include average runoff determination alongside existing IWMP conservation of runoff and environmental flows, as well as proposed land and drainage line treatment estimations for the check dams.

The performance of SWCs adopted under IWMP, evaluated by the SWAT model, was considered as a reference while planning additional SWCs in the watershed. Initially, bunding and trenching were suggested for the entire watershed by excluding the region where they already exist, in line with the criteria established under DSS, shown in Fig. 7. As per the ridge-to-valley approach, preference was given to land treatment, i.e., bunding and trenching, to conserve the runoff at its source, to reduce further soil erosion by improving percolation. By considering the similar impact as in the case of IWMP treatment, runoff conservation was estimated.

Similarly, as a part of drainage line treatment, check dams were proposed based on runoff concentration to further conserve the runoff within the catchment. Fig. 7 shows the locations of proposed check dams based on established criteria under DSS and the residual runoff available for conservation. In combination, this SWC measures effectiveness and will enhance the watershed saturation. In the upstream, land treatments like bunding and trenching proved effective in arresting the runoff at source, where check dams helped in conserving the runoff in drainages, resulting in percolation of water to aquifers as well as base flow.

Table 8: Runoff analysis and proposed SWC measures for watershed saturation[1].

Description	Equation	Value
Overall Annual Average Runoff from the calibrated SWAT model in $m^3.s^{-1}$= (O_{Runoff})	Runoff at the outlet (A+B+C)	1.5743
Conserved runoff through IWMP treatment done in the subwatershed in $m^3.s^{-1}$ = (R_{IWMP})	Impact of Bunding + Trenching + Check dams	0.4120
Runoff can be conserved after deducting Environmental flow (30% of O_{Runoff}) in $m^3.s^{-1}$ = $R_{Available}$	70% of O_{Runoff}	0.9174
Runoff available to conserve after IWMP treatment in $m^3.s^{-1}$ = (R_0)	$R_{Available}$ - R_{IWMP}	0.5053
*Runoff conserved through proposed land treatment in $m^3.s^{-1}$ = R_{Land}		0.2110
Runoff available to be conserved through drainage line treatment in $m^3.s^{-1}$ = R_{DLT}	R_0 - R_{Land}	0.2943
Runoff conserved through a single Checkdam in a year in $m^3.s^{-1}$ = R_{CD}	Considering 850 m^3 of filled 3 times in a year	0.02951
No. of proposed check dams	R_{DLT} / R_{CD}	10
No. of check dams proposed on each drainage line by considering the proportionate runoff		
On Stream A		3
On Stream B		5
On Stream C		2

[1] As per the Ridge to Valley approach, first preference is given to Land treatment (Bunding, trenching, etc.). If runoff is still available, drainage line treatment will be adopted.

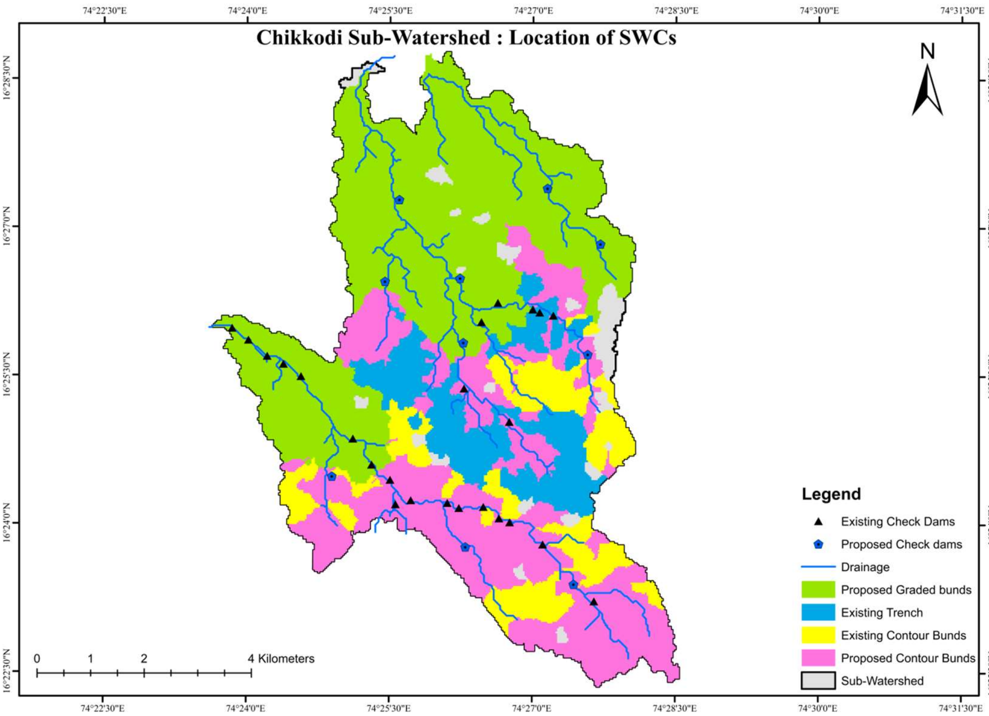

Fig. 7: Proposed implementation plan for Soil and Water Conservation (SWC) measures in the Chikkodi subwatershed (4D7E5) to promote watershed saturation.

The performance of these SWCs depends on various factors, i.e., soil type, rainfall pattern, and watershed features, which may affect the hydrological behavior. All these factors need to be considered while planning the SWC measures in the watershed. This study provides a base for effective watershed management through watershed saturation by adopting SWCs to conserve the runoff. This will result in water availability for a longer period, improved groundwater levels, a reduction in soil erosion, and enhanced health of the watershed. Fig. 7 shows the distribution of established structures with proposed new interventions that emerged from the runoff budget and Sujala-III DSS criteria to reach watershed saturation.

CONCLUSIONS

This study supports the positive impact of introducing SWC methods in the Chikkodi subwatershed, depicting their capacity to enhance watershed saturation, which is obtained through the targeted conservation of runoff, supported by a robust hydrological modeling system. The effectiveness of the SWC technique was studied, and the SWAT model was used to simulate the runoff. Past streamflow records were used for model calibration and validation, accurately reflecting the hydrological activity of the watershed. It was observed that the current SWC practices implemented under the IWMP were effective and resulted in reduced watershed runoff. Specific interventions, such as trenches, check dams, and contour bunds, have demonstrated great potential for capturing and storing runoff. The SWAT model effectively replicated the hydrological outcomes of these interventions, which illustrated the spatial heterogeneity in influence, especially in the reduced runoff recorded at different sub-basin outlets following contour bundling. The model needed to demonstrate that the combined effect of all the SWC measures applied resulted in a significant reduction in the entire watershed runoff by 26.17%. The capability of the SWAT model to accurately predict individual and cumulative hydrological effects at both local and regional scales from distributed SWCs is a critical strength of this study.

Utilizing the proven model capacity, other subsequent SWC interventions were planned under a science-based ridge-to-valley approach to increase watershed saturation. The combined effectiveness of the SWC measures to reduce runoff and improve the water retention capacity of the watershed was demonstrated using SWAT model simulations. The simulation indicated that the implementation of SWCs reduced surface runoff, thus increasing soil moisture reserves and enhancing baseflow. Such realignment to the hydrological regime generates high levels of sustainability value, essentially strengthening the long-term water supply and ecosystem conditions in the semi-arid watershed. However, performance can still fluctuate depending on each site's unique characteristics, eliminating the need for targeted approaches. Based on this study, it is vital to tailor SWC methodologies site by site to achieve saturation in watersheds.

This study provides high-quality, direct knowledge for practitioners to manage watersheds in semi-arid environments. The site-specific SWC planning framework using the ridge-to-valley approach, in combination with the Sujala-III DSS and the integration with the SWAT watershed model, is a strong tool for identifying and implementing site-specific measures of SWC. It enables the identification of the important areas in which the treatment of land and drainage lines should be conducted, and calculates its role in the reduction of runoff, soil moisture, and environmental flow, consequently facilitating the saturation of watersheds and water retention. The findings of this study indicate to policymakers the effectiveness of such an integrated watershed management model-based approach. The capacity to conserve a significant portion of runoff without compromising environmental flow highlights the need for continued investment. The measurable approach helps set saturation goals, allocate resources, and shape policies for long-term water security, erosion mitigation, and productivity in water-stressed regions.

This work acknowledges minor limitations, which are mainly linked with the input data resolution and the simplified character of the hydrological model owing to the necessity of simplification. More research should involve a detailed examination of the distinctive hydrological aspects of each site, assessment of the effects on water quality, and tracking the long-term effectiveness of SWC interventions to establish their sustainability in maintaining the saturation of the watershed and environmental flows. Future research must therefore incorporate the hydrological framework with thorough groundwater monitoring and examine the economy of SWC interventions in supporting long-term sustainability and clarifying implementation strategies.

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