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Original Research Paper

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

Strategic use of Soil and Water Conservation (SWC) techniques is essential for efficient watershed management and managing 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 watershed known as watershed saturation, where maximum generated runoff is conserved while maintaining environmental flow downstream. Using the Soil and Water Assessment Tool (SWAT), the study modelled hydrologic processes in the Chikkodi subwatershed, a semi-arid region. Assessment of existing SWC measures (bunding, trenching, Checkdam, etc.) formed a key baseline analysis; revealed a significant 26.17% runoff reduction due to combined effect of existing SWCs and provided insights for subsequent planning. Based on model outputs, the study recommends land treatment, i.e. bunding and trenching, in identified critical areas, which effectively intercept the runoff at the source and maximize infiltration. Conservation of remaining runoff through drainage line treatments (check dams) are proposed as the next crucial step in the ridge-to-valley strategy. This work highlights the necessity for 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 practices optimization in enhancing watershed water storage in similar semi-arid landscapes.

INTRODUCTION

Water and soil are the most precious resources present on the earth's surface, which contribute to building a balanced ecosystem and promoting sustainable securities of life (Hunt 2005, Pande et al. 2020, Rashmi et al. 2022). Watershed management is the process of planning and directing the use of the soil, water, and other natural resources contained within a watershed to provide the necessary products and services while minimizing the impact (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, check dams, etc., are essential for sustainable resource management that balances the environment by promoting water conservation, regulating the 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 needs comprehensive evaluation to guide effective management plans. Studies quantifying this watershed-level impact are limited. Field experiment data cannot be extrapolated to the watershed scale and have to be tested using mathematical models to assess SWC effectiveness (Raza et al. 2021). Hydrological approaches can be employed for examining the performance of soil and water conservation practices in mitigating or triggering adverse environmental effects. The most generally utilized approach for analyzing the effects of any conservation measures on the hydrological process is hydrological modeling (Liu et al. 2017). Physically based hydrological models, including 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 run-off models include MIKE-SHE, HEC-HMS, APEX, and SWAT (Nesru et al. 2023).

The study of the SWAT model demonstrates that the model is reliable for understanding hydrology. Thus, among several mathematical models, SWAT is chosen to evaluate the impact of SWC measures on watersheds. SWAT is data-intensive, requiring considerable geographical and temporal data (Uniyal et al. 2020), and offers continuous simulation capability 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 helps in water budgeting for hydrological assessment and also forecasts the demand of water for various purposes, such as domestic, agricultural (Bandi and Patil, 2021). Su et al. 2023 used SWAT model to assess the influence of the construction of water conservation projects on runoff from the mountain in different seasons and reported that the model has good applicability in the study area for the assessment of runoff. Strategic planning and agricultural growth can benefit from the SWAT model's ability to forecast future water availability (Verrma et al. 2022). Therefore, using a hydrological model SWAT, is the best way to assess how adopted SWC interventions have affected the hydrological process (Sharma et al. 2024), thus confirming this approach for the present study to assess the impacts of SWCs and hydrological stage of the watershed relevant to treatment.

In the context of this study, watershed saturation is the stage 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, whilst providing for ecological balance desirable amount of runoff called environmental flow to be allowed to flow downstream beyond the watershed boundary.

Achieving this state of watershed saturation, which inherently includes maintaining minimum flow regimes, is critical for ecosystem conservation down the watershed, highlighting the importance of environmental flows (Zeiger et al. 2018). Environmental flows represent the specific amount, quality, and timing of water flows necessary to maintain the viability of freshwater and estuarine ecosystems and the livelihoods depending on them (Yarnell et al. 2020, Hoque et al. 2022). The impact of SWC implementation on environmental flow can be assessed by the changes in average annual flow and flash flood frequency after the 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 state, provides a compelling case study. Prior to 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 intended to bring back ecological balance by conserving and developing the 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 full-scale study had not been conducted to assess their impact on improving the health of the watershed and water retention capacity of the watershed or attaining the desired condition of attainment of saturation in the watershed. Therefore, a rigorous evaluation of the effect of these existing SWCs on the subwatershed's hydrology was necessary as a baseline. Subsequently, to achieve optimum runoff conservation and effectively plan SWCs to move towards watershed saturation, a science-based approach considering existing treatments is essential for sustainable watershed development.

Even though many studies have investigated SWC at the local scale, their implications at the watershed level, particularly in achieving a managed state of watershed saturation through integrated planning, are poorly understood. Quantitatively, this methodology is different than the past planning studies of SWC in India that use the SWAT models, mainly by clearly defining the planning objective investigation, i.e. retention of 70% of the generated runoff (excluding environmental flow) in the watershed and having the necessary environmental flow downstream (Development of DSS under SUJALA III Project, 2019). In order to deliver evidence-based refinement, this framework is based on comprehensive baseline evaluation of existing IWMP-based impacts. Then, criteria are iteratively formulated based on Sujala-III Decision Support System (DSS), to give targeted, site-specific prescriptions, and can recommend, e.g. that in catchments with a runoff of at least 850 m^3, check dams should be given priority in a new SWC. The related recommendations provide specific quantitative thresholds of watershed saturation, out of others, and siting and design specifications of the most significant SWC components and thus support the conversion of the planning into practice.

The scientific novelty of this work is embodied in its unified, science-based approach. This approach integrates authentic field data of geotagged SWCs from the IWMP-19/11-12 project with a calibrated and validated SWAT model. The model is used for both a comprehensive assessment of the existing IWMP SWCs and the subsequent formulation of a ridge-to-valley SWC plan guided by scientific criteria developed by the authorities. This comprehensive framework specifically targets achieving watershed saturation concurrently with 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.

2. MATERIALS AND METHODS

2.1. Study Area

This study was executed in Chikkodi watershed (52.77 km^2) of the middle Krishna basin in southern India. It is located between 74°23′51″ to 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 dry land agriculture, which is susceptible to the irregularities of 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 northern transition zone. The yearly rainfall in the region is around 663 mm. The research area's climate falls under a semi-arid environment (CGWB, 2017). The highest temperature goes from 27°C to 35.7°C, while the minimum temperature ranges from 13.9°C to 20.6°C (CGWB, 2012). The study region includes both flat and steep terrain (Honnannanavar et al. 2023). Fig. 2(b and c) depicts soil and land use maps, which illustrate that agriculture accounts for the vast bulk of land use.

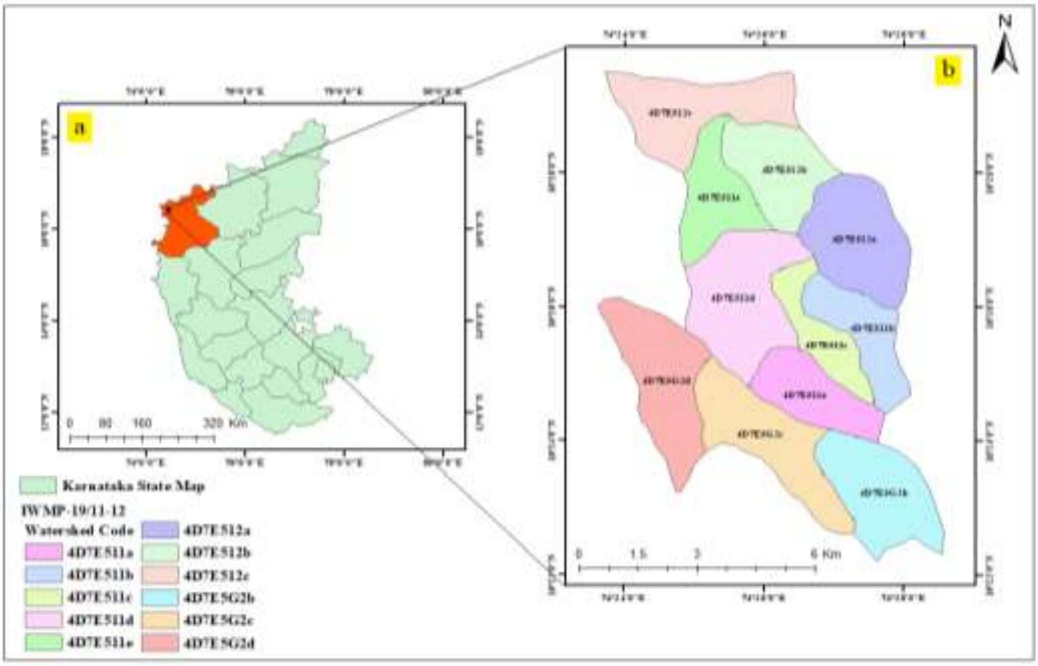

Fig. 1 Study area hierarchy. (a) Location within Karnataka, India (inset). (b) Detailed subwatershed distribution and codes

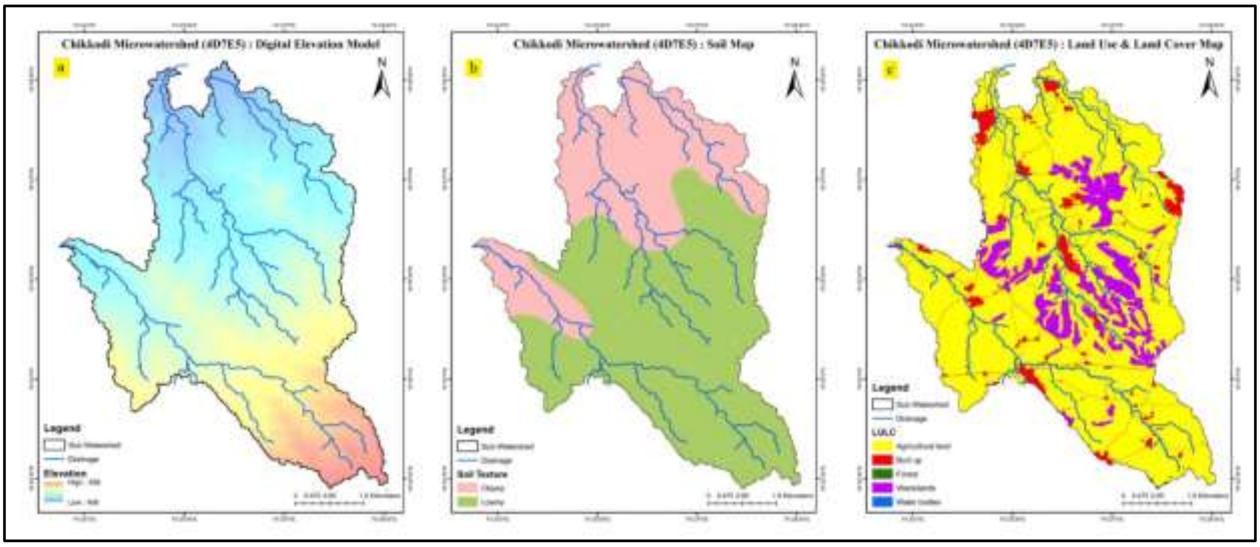

Fig. 2 Hydrological modeling input maps for the Chikkodi subwatershed (4D7E5): (a) Digital Elevation Model (DEM), (b) Soil Map (texture), and (c) Land Use and Land Cover (LULC).

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

2.2. SWC Measures Implemented in the 4D7E5 Microwatershed

SWCs function as sustainable instruments that promote water preservation while controlling water flows at the surface and below, and minimize soil erosion, which advances sustainable resource management (Yan et al. 2023). Soil losses across the 4D7E5 watershed measure between 900-1100 Mg/km^2/year 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. The 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 with elevation lines are used (Madegowda et al. 2021). Such bunds function best in areas that experience rainfall below 800 mm per year while having porous soil foundations. The study region receives adequate rainfall (663 mm) annually on its exclusively agricultural land, where clay-loam soil predominates, which makes contour bunds a suitable practice. Check dams function as structural SWC elements constructed using stones to both decrease rainwater runoff and support soil infiltration that provides water for irrigation to the nearby agricultural fields. Every dimension of a check dam significantly enhances its ability to minimize rainwater overflow and capture sediment.

Under project IWMP-19/11-12 through watershed development by the Government of Karnataka, the treatable area of 46 km² has received earthen field bunds and trenches treatment according to project specifications. As a part of 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 extent is shown in Fig. 4.

2.3. SWAT Model

SWAT represents a watershed simulation model that arose from 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 since 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 (Arnold et al. 2011, 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 ith day (mm)

E_a = evapotranspiration on ith day (mm)

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

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

2.4. Input Data for the SWAT Model

A digital elevation model (DEM) of 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 https://swat.tamu.edu/ website (Global dataset for SWAT 2012) for 20 years (2000-2020). Furthermore, the monthly stream flow 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).

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's outlet, the simulation period (2004–2020) was used as a baseline period. As a result, the SWAT model was calibrated and verified for this time frame.

2.5. SWAT Model Performance Assessment

A performance measurement method calculates the model output rate variation when its input parameters experience variations (Moriasi et.al. 2007). The evaluation process of models directly depends on their performance assessment requirements. The model evaluation demonstrates how well the models perform in the historical reference period in comparison to observed river flow and other factors (Najafzadeh et al. 2023). By calibrating and validating the model findings against observable values, the model performance is evaluated.

Manual as well as auto-calibration and validation can be done 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, then examining observed values against SWAT calculated values and modifying parameters within their relevant ranges based on published literature until optimal correlations emerge. The model performance evaluation used the coefficient of determination (R2) and Nash–Sutcliffe coefficient (NS; Nash and Sutcliffe, 1970) along with per cent bias (PBIAS) (Moriasi et al. 2012). The Moriasi et. al. (2007) proposed general performance parameters are given in Table 1.

Table 1 Performance parameter for 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

The Chikkodi watershed underwent model calibration for runoff through manual as well as auto-calibration (SWAT-CUP) techniques throughout twenty years from 2000 to 2020 using a three-year warm-up phase from 2000 to 2003. Monthly stream flow information served as the basis to calibrate as well as validate the model.

The model calibration spanned 7 years from 2004 to 2011, while the validation took place during the subsequent 9 years from 2011 to 2020. The proper parameters went through adjustments until model predictions for monthly stream flow matched observed data at watershed outlet locations.

2.6. 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 becomes attuned. The flowchart describes how to determine 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 given in Fig. 3-b.

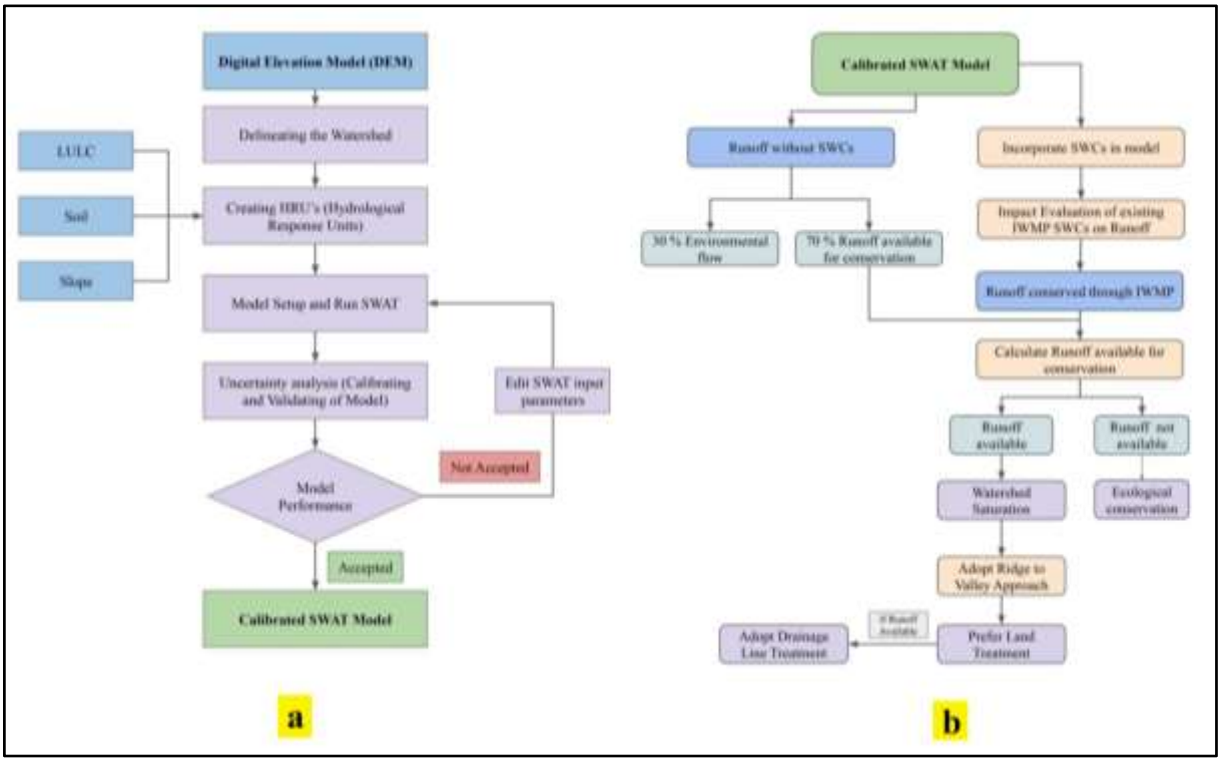

Fig. 3 Methodological flowchart for (a) SWAT model implementation and (b) Decision-making framework for watershed saturation using SWC measures derived from SWAT modeling.

2.6.1. Modeling SWC Impacts on Runoff in SWAT

The sustainable practice of SWC structures reduces soil loss as a result of soil erosion, with surface water flow regulation to improve water conservation in the environment. Sustainable resource management becomes possible because of SWC measures (Melaku et al. 2017). SWC structures are already 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 method, resulting in the prevention of channel or gully formation at the downstream side (Nabi et al.2020). The SWC methods, such as contour bunding, trenching, and terracing, as well as structures such as check dams, farm ponds, and nala bunds, controlled soil erosion and enhanced moisture retention, promoting agricultural development.

The hydrological model SWAT enables users to model SWC systems through specified model parameters. The model simulations used parameter value changes based on Table 2 to simulate the process of SWCs. The research area has approximately 60 sub-basins where contour bunds were implemented (Fig. 4). A SWAT-based runoff simulation was conducted by adjusting suitable model parameters. Table 2 contains information about SWC types while providing the SWAT input parameters used alongside suggested values for good conditions and corresponding references.

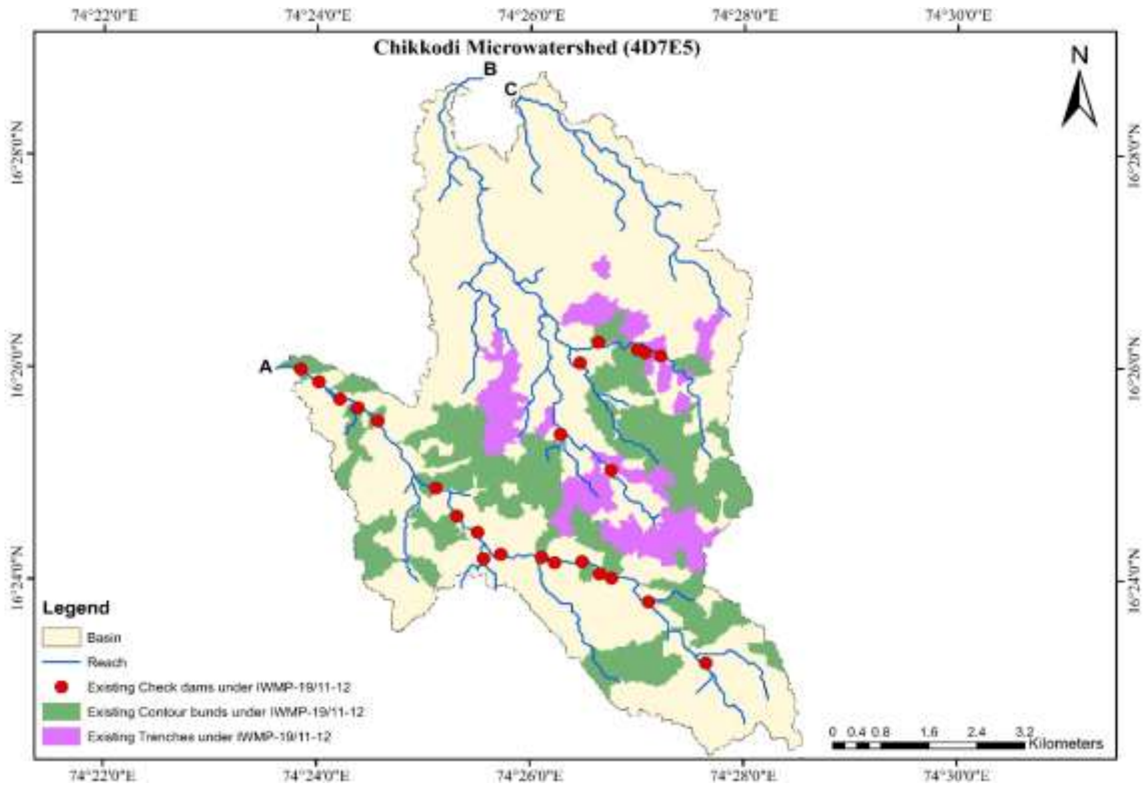

Fig. 4 Map of the Chikkodi subwatershed (4D7E5) showing the spatial extent of existing SWC infrastructure implemented through the IWMP (19/11-12).

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

A total of 21 check dams were implemented in the micro-watersheds to control 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. SWAT represents check dam as conceptual ponds that require modifying PND_FR along with PND_K, PND_PSA, and PND_VOL. 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.

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

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

2.6.2. Runoff Conservation Strategies for Watershed Saturation

The 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 the excess runoff and reduce soil erosion. By considering runoff conservation strategy, this study proposes a scientific way to achieve watershed saturation by adopting SWCs. This study offers a scientific way for planning SWCs to achieve watershed saturation by conserving runoff.

2.6.3. Estimating Runoff with the SWAT Model

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

2.6.4. Strategic Runoff Allocation for Environmental Needs and Conservation

Ensuring environmental sustainability was 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 rest of the 70% was to be conserved. This allocation matches the country-wide recommendations of the Ministry of Environment, Forest & Climate Change (MoEF&CC) who 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, dominated by monsoons, this practical division serves the objectives of conservation in addition to maintenance of vital downstream flows. Hence, 30% of the initial runoff was set aside for environmental flow. Through SWC procedures, the remaining 70% of the runoff was intended to be conserved. The efficiency of 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 IWMP SWCs from the total runoff.

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

The ridge-to-valley strategy was used to plan SWC measures further. Catching the runoff and encouraging infiltration at its source is the objective of this strategy. Initially, except for the places where structures were already in place, the whole watershed was to be covered by bunding and trenching. The SWAT model was used to evaluate the impact of this scenario on conserving runoff. It was suggested to treat drainage lines by building check dams to further save the leftover runoff. After bunding and trenching, the positions of check dams were established based on the distribution pattern of 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 the state's large rainfed areas. The process of creating a conservation plan involves matching various conservation measures to the site-specific potentials and restrictions of the place and then selecting the most efficient option based on the available criteria. The quantity of rainfall, the kind of landform, the soils, the land use, and other factors all have a role in determining the selection of treatment type. Bunding, terracing, and trenching are the main field-level treatments used to conserve soil and water.

2.6.6. 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, as well as other line departments in the state of Karnataka. With this, authorities can able to 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: https://www.sujala3lri.karnataka.gov.in/DSSCriteriaParameter/)

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

2.7. Data Limitations and Uncertainties in Model

The major sources of uncertainties 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, whose spatial resolution is insufficient to represent precipitation variations on a local scale, which will bring uncertainty as runoff and water balance estimates are obtained. The 30m DEM is appropriate to analyze the watershed but it may not satisfactorily bring out finer topographic details which 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 possibly could fail to reflect the complexity of land cover (and soil properties) found in the Chikkodi subwatershed. These simplifications may cause inaccuracy in evaluating important parameters of the SWAT model such as CN values, soil water hosting capacities and hydraulic conductivities to cause uncertainties in determining the accuracy of determining the exact effects of SWC measures on local water balance components. In spite of such inherent ambiguities in data, the best possible datasets were used.

3. RESULTS AND DISCUSSION

In the present study, the SWAT model was used for the hydrological planning of SWC measures in Chikkodi subwatershed, which experiences a semi-arid climate. Many studies on hydrological evaluation and water resource management in semi-arid regions 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. On the other hand, 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 resources management. For semi-arid watershed in Turkey, Aibaidula et al. (2022) adopted 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.

3.1. Streamflow Model Performance: Calibration and Validation

Calibration was done for eight years starting from 2004 to 2011 to match simulated results with observed data. The sensitive parameters were identified and adjusted to obtain better calibration. This is confirmed by knowing the R^2 and NSE values between observed values and simulated results and must be within the allowable limits. During the process, the sensitive parameters are adjusted to achieve maximum model efficiency which is shown in Table 4.

Even though it is well acknowledged that measured data are fundamentally uncertain, model evaluation tends to neglect this uncertainty into account, possiblydue to a lact of required data. Observations were taken at Sadalga gauge station throughout the year from 2000 to 2020. A comparison together with correlation analysis was established between SWAT simulation results using seasonal runoff data for the mentioned year and actual measured data. The procedure included both manual and auto-calibration steps. The performance of model for both manual as well as auto calibration is shown in

Table 5.

Table 4 Identified sensitive parameters adjusted during 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

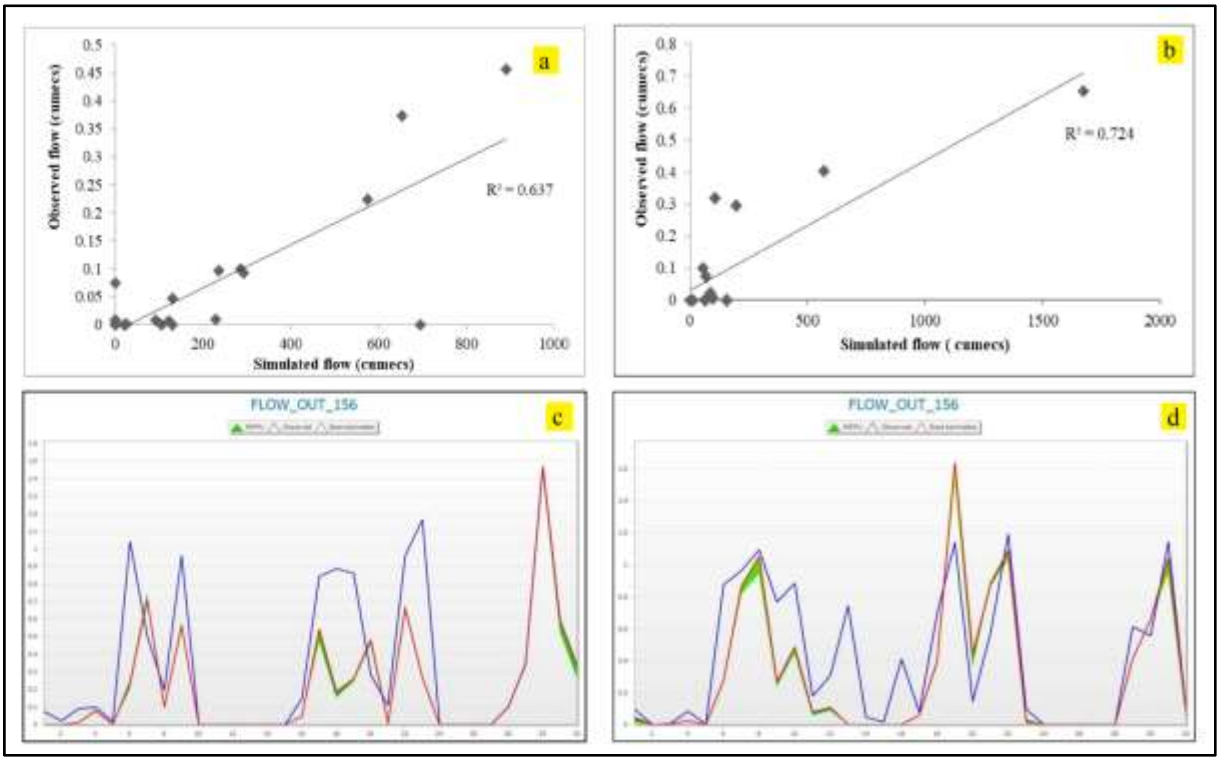

Fig. 5 Evaluation of SWAT model performance for stream flow simulation (a) Manual Calibration scatter plot (b) Manual Validation scatter plot (c) Auto-calibration hydrograph with 95% PPU. (d) Auto-validation hydrograph with 95% PPU. Calibration periods (2004-2011) and validation period (2012-2020)

Parameters that are essential in determining the effectiveness of the model such as NSE values gave an initial result of 0.41, which is an indication of a Moderate performance in the manual calibrations. Nonetheless, to increase model accuracy and resilience, calibration and validation were improved even further through auto-calibration by SWAT-CUP. This considerably enhanced the NSE values: 0.41 to 0.53 during calibration and 0.65 to 0.72 during validation.

Although the first manual calibration gave a 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 values of improved NSE of 0.53 and 0.72 show that model gave performance that was rated as Satisfactory to Good, a level that is adequately acceptable in carrying out hydrological modeling in areas that are complex, data deficient or semi-arid in nature (Moriasi et. al. 2007). More importantly, to 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.

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

3.2. Hydrological Impacts of Implemented SWC Measures

The spatial variation in annual average runoff without any treatment in the watershed is represented 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 the runoff generated within the watershed was flown out of the watershed with sediments. In this context, there was a scope available to conserve the runoff by adopting various SWCs within the watershed.

3.2.1. Impact of Contour Bunds on Runoff

In this research region, contour bunds have been used in around 60 sub-basins. By altering the appropriate SWAT parameters as outlined in Table 2, the effect of these contour bunds on simulating runoff has been assessed. According to the analysis conclusions, the implementation of this specific SWC solution had an acceptable impact since 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 there was less area adopted under bunding treatment. This spatial variation in simulated runoff reduction demonstrates that the SWAT model effectively captured the localized impact of contour bunding within the watershed.

3.2.2. Impact of Trenches on Runoff

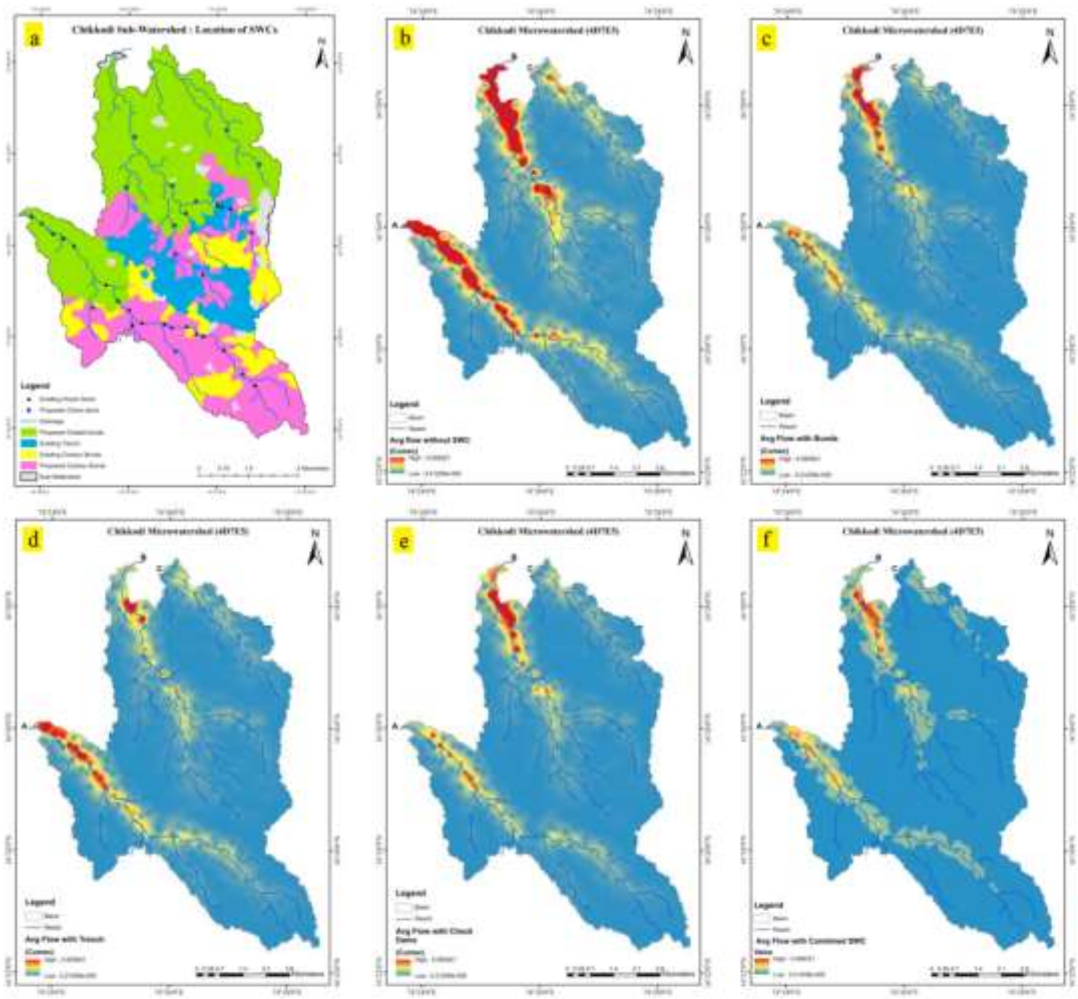

Fig. 6 Impact of SWC measures on average seasonal flow in the Chikkodi subwatershed (4D7E5). (A) Locations of existing and proposed SWCs. (B) Average seasonal flow without SWCs. (C) Average seasonal flow with bunds. (D) Average seasonal flow with trenches.

This study has assessed the effects of trench installation on the simulation of runoff. According to Table 2, the HRU, parameter SLSUBBSN, and mgt. (Management) parameter USLE P has been changed. SLSUBBSN adjusted to 10m for slopes between 10% and 20% and 9.1m for slopes more than 20%. Trenches have decreased runoff by 6.33% owing to their deployment in the research region, according to the model simulation findings. It demonstrates that trench installation has a better effect on runoff. Fig. 6– d and

Table 5 illustrate the decreased runoff. The 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 is observed at outlet A, as trenches were not adopted in that area.

3.2.3. 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 in the research location as per IWMP-19/11-12. SWAT has a conceptual visualization of the pond as a check dam, so 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 while comparing with Fig. 6 - a, as the majority of check dams adopted on drainage with outlet B. Minor variation is observed at outlet A in comparison with outlet B, as only a few check dams were placed on drainage B. It is indicated that check dams are quite helpful in conserving runoff in significant amounts.

3.2.4. Combined Impact of SWCs on Runoff

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%

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 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

3.3. Planning of SWCs to Achieve Watershed Saturation by Runoff Conservation

This study focuses on planning SWCs for watershed saturation through runoff conservation. The impact of existing IWMP SWCs on runoff was assessed within 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 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 criteria below were used to propose 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. By assuming the impact of existing IWMP structures, in the correlation same structures were proposed in this study to conserve the remaining runoff out of the available runoff after IWMP treatment. As per the ridge-to-valley approach, preference was given to the 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 volume of runoff will be conserved by structures adopted in drainage line treatment, preferably check dams. This approach will result in watershed saturation. In this study, the same line of 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 check dams.

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

Description	Equation	Value

[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.

Overall Annual Average Runoff from calibrated SWAT model in m^3/s = (O_{Runoff})	Runoff at the outlet (A+B+C)	1.5743
Conserved runoff through IWMP treatment done in the subwatershed in m^3/s = (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 = $R_{Available}$	70% of O_{Runoff}	0.9174
Runoff available to conserve after IWMP treatment in m^3/s = (R_0)	$R_{Available}$ - R_{IWMP}	0.5053
*Runoff conserved through proposed land treatment in m^3/s = R_{Land}		0.2110
Runoff available to be conserved through drainage line treatment in m^3/s = R_{DLT}	R_0 - R_{Land}	0.2943
Runoff conserved through a single Checkdam in a year in m^3/s = R_{CD}	Considering 850 m^3 of volume 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

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 the line of 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.

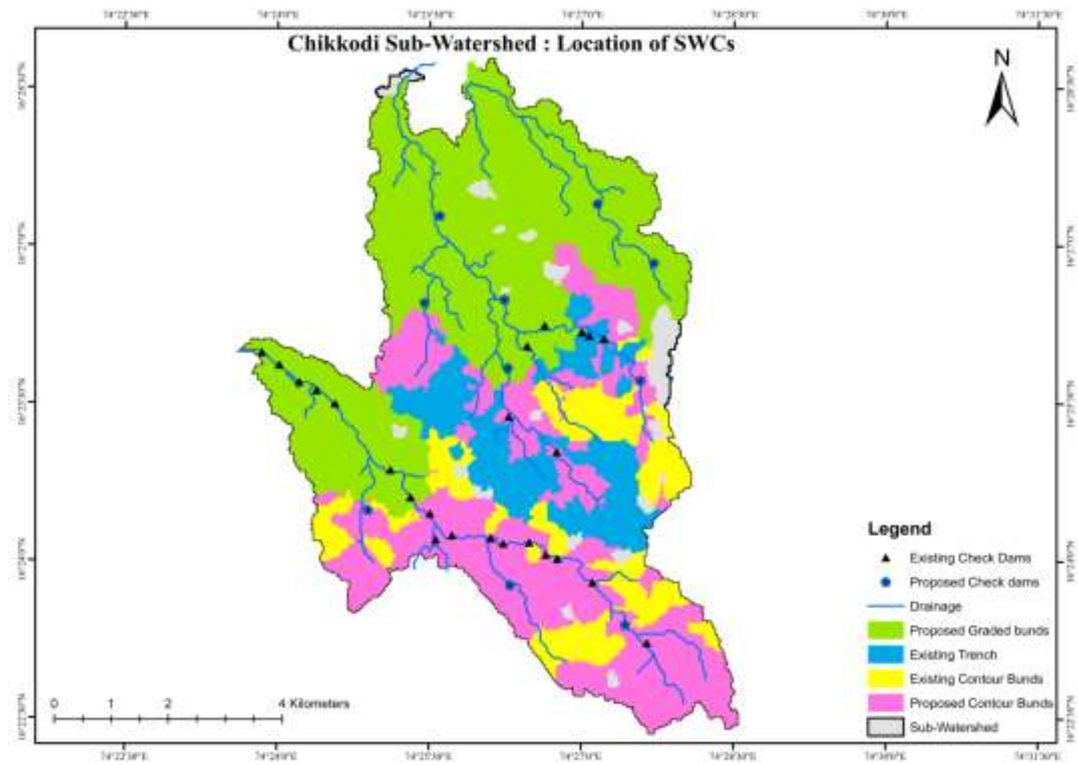

Fig. 7 Proposed implementation plan for Soil and Water Conservation (SWC) measures in the Chikkodi subwatershed (4D7E5) to promote watershed saturation.

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, 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.

4. CONCLUSIONS

This study supported the positive impacts of introducing SWC methods in Chikkodi subwatershed, depicting their capacity to enhance watershed saturation, which is obtained through 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 runoff. Past streamflow records were used for model calibration and validation, thus accurately reflecting the hydrological activity of the watershed. It was observed that the current SWC practices that were implemented under the IWMP were effective and had resulted in reduced watershed runoff. Some specific interventions, like trenches, check dams, and contour bunds, 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 bunding. It was imperative that the model demonstrated that the combined effect of all the SWC measures applied had resulted in a significant reduction of the entire watershed runoff by 26.17%. This 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 research.

Utilizing the proven model capacity, other subsequent SWC interventions were planned under a science-based, ridge-to-valley approach to increase watershed saturation. The SWC measures combined effectiveness to reduce runoff and improve the water retention capacity of the watershed is intensely demonstrated by the SWAT model simulations. The simulation indicate that the implementation of SWCs has managed to reduce surface runoff, thus provoking increased soil moisture reserves and enhanced baseflow. Such realignment to 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 the targeted approaches. It is vital, based on this study, to tailor SWC methodologies site by site to achieve saturation in watersheds.

The study provides high-quality, direct knowledge, and practitioners to manage the watershed 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 integrated with the SWAT watershed model stands as a strong tool to identify and implement site-specific measures of SWC. It enables identification of the important areas in which the treatment of land and drainage line should be conducted, calculates its role in the reduction of runoff, soil moisture, and environmental flow consequently facilitating saturation of watersheds and water retention. The finding of the study indicates to policymakers the effectiveness of such an integrated watershed management model-based approach. The capacity to conserve significant portion of runoff without compromising environmental flow highlights the need of continued investments. The measurable approach helps to set the saturation goals, allocate resources, and shape policies to long-term water security, erosion mitigation, and productivity in water-stressed regions.

This work acknowledges minor limitation, which is mainly linked with the input data resolution and the simplified character of the hydrological model due to the necessity of simplification. More research should involve detailed examination of the distinctive hydrological aspects of each site, assessing 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. Research in the future 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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