International Journal of Scientific Research in Engineering & Technology
Special Issue, Volume 5, Issue 4 (July-August 2025), PP:75-84.
https://www.doi.org/10.59256/ijsreat.20250504C13
Recent Advances in Civil Engineering and Technology (REACT)-2025
www.ijsreat.com ISSN No: 2583-1240

# Evaluation of Best Management Practices in Reducing Runoff at Meenachil River Basin

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**To Cite this Article:** *Lekha B.S[1], Smitha Mohan.K[2], "Evaluation of Best Management Practices in Reducing Runoff at Meenachil River Basin", International Journal of Scientific Research in Engineering & Technology Volume 05, Issue 04, July-August 2025, PP: 75-84.*

**Abstract:** *The Meenachil River Basin faces critical challenges in managing rainfall runoff, which often leads to adverse effects such as soil erosion and flooding. Effective management of runoff is essential for mitigating these issues and for improving the overall health of the watershed. Implementation of Best Management Practices (BMPs) can reduce runoff and improve water quality of the watershed. The primary objective of this study is to identify the most effective management practice to reduce runoff in the Meenachil river basin. Hydrological simulations of the watershed were performed using the SWAT model. To ensure accuracy sensitivity analysis, calibration, and validation of the model were conducted using SWAT-CUP software, employing the SUFI-2 (Sequential Uncertainty Fitting) technique. The model was calibrated using streamflow data of 13 years from 2001 to 2014 and validated another set of data of 3 years from 2015 to 2017.The Nash Sutcliffe Efficiency (NSE) value for calibration and validation (0.55 and 0.66) shows the models good performance. BMPs implemented in this study bench terrace, contour farming, contour bunding, filter strips. The annual runoff for the river basin was 93.074mm. This was reduced to 82.93, 82.93, 87.72, 92.57, 82.7, 82.7 and 87.25 respectively by bench terrace, contour bunds, contour farming, and filter strip, combination of bench terrace and filter strip, combination of contour bunding and filter strip, and combination of contour farming and filter strip respectively. The reduction efficiency was calculated and it was observed that combination of contour farming and bench terracing with filter strip achieved highest runoff reduction. These results revealed that the combined implementation of various BMPs significantly reduced runoff compared to individual BMPs. These finding underscores the effects of integrating multiple management practices. The study offers valuable insights for sustainable watershed management in the Meenachil River Basin.*

**Key Word:** *Best management practices (BMPs), SWAT, runoff reduction, watershed management.*

## I.INTRODUCTION

Although 71% of the Earth's surface is covered with water, 96.5% of it is seawater. Only 3.5% of the water on Earth's surface is freshwater, and of that, 2.5% is unavailable for use. This portion is in the form of glaciers, ice caps, may be in the atmosphere or soil, or it may be too polluted or too deep underground to extract. Therefore, only 0.5% of the Earth's water is accessible and suitable for human consumption. Since water is essential for life and plays a critical role in human, environmental, and economic systems, conserving this precious resource is crucial. Excessive use and wastage of water can lead to water scarcity. Water wastage often occurs due to uncontrolled runoff, which prevents rainwater from infiltrating into the soil and being effectively utilized. Runoff occurs when water flows over the land surface as surface water rather than being absorbed into the ground as groundwater or lost through evaporation. It typically happens when the amount of precipitation exceeds the soil's capacity to absorb. Several factors influence the generation of runoff, such as rainfall intensity, duration, and distribution, size, shape, and slope of the watershed, land use, and soil characteristics such as infiltration capacity and moisture content. Runoff can lead to various environmental issues. It can cause soil erosion and land degradation. During the monsoon season, heavy runoff often results in flooding. As water flows over land surfaces, it carries agricultural chemicals, untreated sewage, and industrial effluents into rivers and other water bodies. This not only pollutes the water but also degrades water quality and harms aquatic life. This can be controlled by utilizing Best Management Practices (BMPs). Best Management Practices (BMPs) are techniques, methods, or strategies used to manage and reduce the impact of runoff, flooding, and scarcity. It involves implementation of strategies and processes that are widely recognized as the most effective and efficient means to achieve organizational objectives, ensuring quality, compliance, and continuous improvements. There are two types of BMPs structural BMPs and agricultural BMPs. various criteria have to be evaluated before selecting Best Management Practices (BMPs) to be ensure effectiveness, practicality, and sustainability in reducing runoff. Criteria for selecting the best BMP for runoff reduction are land slope, soil depth, rainfall and land use. Structural BMPs involve physical constructions or engineered systems such as check dams, contour bunds, percolation tanks, and sediment traps, which are designed to control runoff, reduce erosion, and enhance groundwater recharge and non-structural BMPs focus on planning, policy, and behavioral changes, including land use management, crop rotation, afforestation, public awareness programs, and proper agricultural practices, which aim to minimize the generation of pollutants at the source and promote sustainable resource use without relying on built infrastructure. Together, these BMPs play a complementary role in achieving long-term soil and water conservation goals. The Meenachil River Basin faces significant challenges like soil erosion due to increasing runoff, and flooding, making it necessary to introduce runoff management practices. The rapid growing population, urbanization, and agricultural activities in the region make these issues worse, which results in frequent flooding and inadequate water storage. In the study conducted by International Water Management Institute (IWMI) stated that, by 2030 the total water demand in India will increase by 32% while, the average per capita water availability will decline to 1140 $m^3$. Therefore, it is essential to examine these issues at watershed to develop policies and plans for ensuring a sustainable future for our next generation. The main objective of the study is to suggest the most effective management practices (Best Management Practices (BMPs)) to resolve the issues of soil erosion and to conserve water in the study area. Also, to Find out the best management practice with highest runoff reduction. This study aims to address all these challenges by developing a comprehensive runoff management framework, evaluating and optimizing best management practice scenarios, and providing science-based recommendations for decision-makers. The expected outcomes of this study include reduced flooding and soil erosion, and to improve water balance components, and inform decision-making for sustainable water resource management.

## II.MATERIAL AND METHODS

**Description of the study area:**

Meenachil river basin a sub-watershed of Pamba is selected for the study since it faces soil erosion problems. It is also known as Meenachilaar, Kavanar, or Valanjar. The name Meenachil is derived from the name of Goddess Meenakshi of Madurai. It is situated in the southwestern part of Kerala, in Kottayam district. It is the major river in Kottayam district and is a west flowing river like all other river in Kerala.The length of the river is 78 km. The river has 38 tributaries, the main tributaries are Kurishumalai, Thrikovil, Chattapuzha, Kadapuzha, Kalathukadavu Aar, Poonjar, Chittar,Lalam and Meenadam Aar.The watershed covers an area of 1,272 km² lies between 09º26’24” and 09º51’00” N and 76º 22’12” and 76º55’12” E . The river originates from Kurishumala near Vagamon in the Idukki district and flows through Erattupetta, Palai, Ettumanoor and Kottayam and empty’s itself into Vembanad lake in Kumarakom.This river basin is selected since it is a subbasin of Pamba watershed where there are many reports showing soil erosion in this area. Also, during the monsoon, this river floods low-lying areas, and during the summer, basin experiences serious water shortage. A large portion of population of Kottayam district are dependent on the Meenachil River and its tributaries for drinking, agriculture, and trade. A significant amount of the basin is made up of rubber plantations, agriculture (rice, seasonal crops), and unplanned urban growth, all of which depend on sufficient water supply. For this river, which suffers from soil erosion, scarcity of irrigation water, salt water intrusion, and water contamination because of sewage discharge, water management measures are crucial.

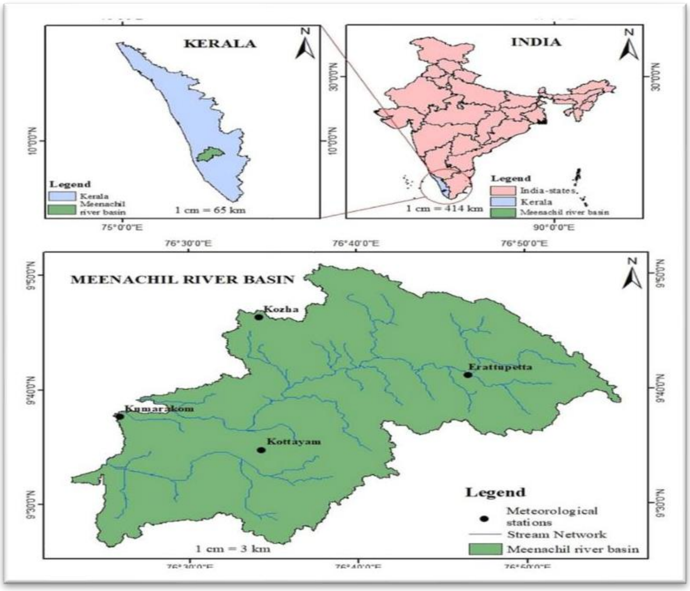



*Fig 1: Location of study area*

**Data used:**

Data collection is one of the initial steps. It ensures the accuracy and reliability of the analysis. Various datasets, including spatial, hydrological, meteorological, and land-use information, to effectively model and assess the Meenachil river basin using SWAT. Digital Elevation Models (DEM) for terrain analysis, land use/land cover (LULC) maps, soil data, and hydro-meteorological records such as rainfall, temperature, and streamflow observations. Proper pre-processing and validation of the collected data are essential to ensure consistency and improve model performance in the study. Table 1 shows the types of data and their sources. Meteorological data include daily precipitation data, river discharge data, maximum and minimum temperature, wind speed, solar radiation and relative humidity. The daily precipitation data of four rain gauge station Kottayam, Kozha, Kumarakam and Kanjirappily was obtained from NASA Power. The maximum and minimum temperature, wind speed, solar radiation and relative humidity was also obtained from NASA Power. Daily river discharge data from Kidangoor station was obtained from India Water Resources Information System (WRIS). These data were collected for the period 2001 to 2023.DEM of the study area was downloaded from United States Geological Survey (USGS) earth explorer. Soil data was acquired from the Soil Database from FAO (Food and Agricultural Organization) and LULC map was derived from Esri sentinel-2 land cover.

**Table 1 Data and their sources**

| S.No | DATA | SOURCE |
|---|---|---|
| 1. | Digital Elevation Model (DEM) | United States Geological Survey(USGS) https://earthexplorer.usgs.gov/ |
| 2. | Soil Map | Food and Agriculture Organization(FAO) |
| 3. | Land use land cover map | Esri sentinel-2 land cover |
| 4. | Daily Precipitation Data (mm) | NASA Power https://power.larc.nasa.gov/data-access-viewer/ |
| 5. | River discharge data | India Water Resources Information System https://indiawris.gov.in/wris/#/ |
| 6. | Maximum and Minimum temperature (°C) | NASA Power https://power.larc.nasa.gov/data-access-viewer/ |
| 7. | Solar radiation (MJ/m²) | NASA Power https://power.larc.nasa.gov/data-access-viewer/ |
| 8. | Relative humidity (%) | NASA Power https://power.larc.nasa.gov/data-access-viewer/ |

**SWAT model:**

The Soil and Water Assessment Tool (SWAT) was developed by the United States Department of Agriculture-Agriculture Research Service (USDA ARS). It is an eco-hydrological model, which has been widely used in simulating the response of various land use management strategies and is competent enough in evaluating the climate change impacts on water quality and quantity in agricultural catchments. It is also used in simulating water quality of agricultural catchments in different parts of the world. Weather, surface runoff, return flow, percolation, evapotranspiration, transmission losses, storage of pond and reservoir, crop growth and irrigation, groundwater flow, reach routing, nutrient and pesticide loading, and water transfer are all included in this hydrological model. SWAT integrates with GIS platforms such as ArcGIS and QGIS through interfaces like Arc SWAT and QSWAT, enable spatial analysis and visualization of watershed processes. It allows users to simulate the impact of various land management practices, land-use changes, and climatic variations on water resources, sediment transport, and nutrient dynamics within a watershed. SWAT is particularly effective for long-term simulations, supporting sustainable water resource planning, pollution control, and runoff management by enabling scenario analysis and providing insights into complex watershed interactions. SWAT integrates physical processes like precipitation, evapotranspiration, surface runoff, infiltration, and groundwater flow to simulate the complete water cycle. Governing equation for SWAT software is water balance equation. It is used to predict the hydrology at each HRUs.

The general equation of SWAT model is

$$SW_t = SW_O + \sum_{i=1}^{t} (R_{day} - Q_{surf} - ET - W_{perc} - Q_{gw})$$

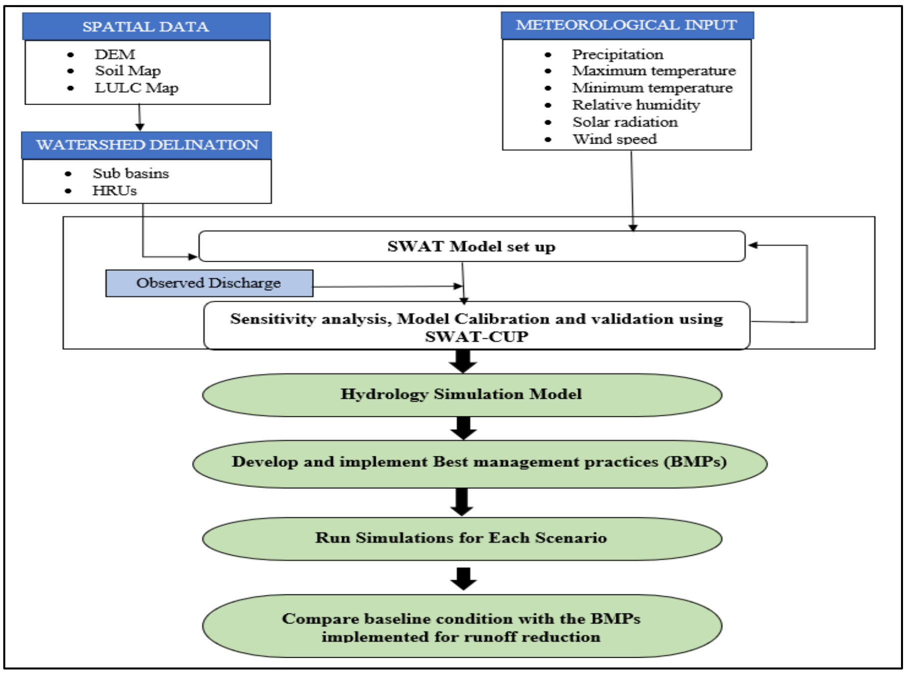



*Fig 2: Flow chart of the methodology*

Here, $SW_0$ is the initial soil water content (mm/day), $SW_t$ is final soil water content (mm/day),t is the time in (day), $R_{day}$ is the precipitation (mm/day), $Q_{surf}$ is the surface runoff (mm/day), $ET$ is the evapotranspiration (mm/day), $W_{perc}$ is percolation (mm/day), and $Q_{gw}$ is the amount of return flow (mm/day). In this study, the Soil and Water Assessment Tool (SWAT) was employed to simulate and evaluate the hydrological behavior of the Meenachil River Basin, with a focus on assessing the effectiveness of various Best Management Practices (BMPs) in reducing runoff. The process began with the collection and preparation of spatial data, including a DEM, LULC map, soil map, and slope map and meteorological data. DEM was used to delineate and divide the watershed into sub basin and by overlaying LULC map, soil map and slope map Hydrologic Response Units (HRUs) were formulated. Meteorological data including precipitation, maximum and minimum temperature, wind speed, solar radiation, and relative humidity were incorporated into the model to simulate hydrological processes including surface runoff, infiltration, evapotranspiration, lateral flow, and groundwater contribution. The overall methods used in this study was summarized in Fig 2

**Calibration and validation:**

The ArcSWAT model was calibrated and validated using discharge data from Kidangoor river gauging station over 22years. The model was calibrated and validated using data from 1990 to 2004 and 2005 to 2014. A large number of model parameters were estimated from various sources, influencing simulation results with varying weights. As a result, SWAT-CUP was used before calibration to identify the sensitive parameters using Global sensitive approach). The SWAT-CUP is linked with the Sequential Uncertainty Fitting method (SUFI-2) to per-form sensitivity analysis and rank the inputted parameters based on their order of sensitivity by comparing observed and simulated results. SUFI 2 is a global optimization algorithm for identifying uncertainty in parameters, then calibrating and evaluating the uncertainty of watershed models. It is simple to use and can handle a large number of parameters. Numerous studies concluded that SUFI is a powerful and time-saving sediment yield calibration tool. SWAT parameters are classified into six groups: basin, sub-basin, main channel, HRU, groundwater, and soil. To determine the sensitivity of a parameter, two statistical measurements P-value and t stat are used. The sensitivity range is represented by the t-value, but the significance of sensitivity is represented by the P-value. We evaluated SWAT model performance by comparing observed and simulated outputs using Nash-Sutcliffe modeling efficiency (NSE) and coefficient of determination (R). The NSE is calculated as a ratio of simulated to observed variances, ranging from ∞ to +1. While NSE values less than 0.5 indicate an unsatisfactory model, values greater than 0.75 imply that model simulations are very good. The R 2 value ranges from 0 to 1, representing the relationship between the simulated and observed data. If the R2 value is one, the simulated and observed data are equal. If R2 is zero, it indicates no correlation between the simulated and observed data. Table 2 shows the statistical parameter and its performance rating and value ranges used for calibration and validation.

**Table 2: Value range and model performance ratings**

| Performance Rating | NSE | $R^2$ |
|---|---|---|
| Very good | $0.75 < NSE \le 1.00$ | $0.7 \le R^2 \le 1$ |
| Good | $0.65 < NSE \le 0.75$ | $0.6 \le R^2 \le 0.7$ |
| Satisfactory | $0.50 < NSE \le 0.65$ | $0.5 \le R^2 \le 0.6$ |
| Unsatisfactory | $NSE \le 0.50$ | $R^2 < 0.5$ |

**Best management practices for runoff reduction:**

Generally, Best management practices refer to a set of techniques and strategies that are implemented to achieve specific goals, often in a sustainable and efficient manner. These practices can be applied across various fields, including environmental protection, agricultural production, and business operations. Here BMPs are designed to control runoff, reduce soil erosion, and to improve water balance components. BMPs are broadly classified into two main categories, structural BMPs and non-structural BMPs. The selection of appropriate Best Management Practices (BMPs) for effective soil and water conservation requires a systematic evaluation of land slope, soil properties, rainfall patterns, cropping systems, and economic feasibility to ensure both environmental sustainability and agricultural productivity, as there are many types of BMPs available. In this study, a combination of structural and non-structural BMPs was adopted based on land slope, rainfall intensity, and land use characteristics to ensure site effectiveness and sustainability. Structural BMPs such as bench terracing and contour bunding are engineered solutions that physically alter the landscape to slow down runoff, promote water retention, and reduce sediment transport on sloped terrains. Bench terracing transforms steep slopes into level platforms, effectively decreasing water velocity and encouraging infiltration, while contour bunding involves the construction of embankments along contour lines to interrupt surface flow and trap sediments. Non- structural BMPs, including contour farming and filter strips, provide ecological solutions with lower implementation costs. Contour farming aligns agricultural activities with the natural contours of the land, reducing runoff velocity and encouraging moisture retention in the root zone. Filter strips, which are vegetated buffer zones located between agricultural fields and water bodies, act as biofilters that trap sediments, nutrients, and pollutants before they enter the hydrological system. Multiple simulations are conducted for different BMP scenarios to assess their impact on runoff and soil erosion. Using the four BMPs we have created seven scenarios therefore a total of eight scenarios were made and used to conduct this study. The eight scenarios are listed in the Table 3 below. Scenario 1 is baseline represents the the current or existing conditions of the watershed without implementing any BMPs. It serves as a reference scenario to evaluate the impact of other scenarios. Bench terracing is the second scenario it involves creating step-like structures on sloped agricultural land. It significantly reduces runoff velocity and soil erosion. Scenario 3 is represented by contour bunding it involves construction of embankments along the contour lines of the slope. It slows down surface runoff, enhances infiltration, and traps sediment, thereby reducing soil loss. Scenario 4 is contour farming here ploughing and planting of crops is done along the natural contours of the land. This technique reduces water runoff, increases water infiltration, and helps in soil conservation. Filter strip serves as scenario 5 here vegetated buffer zones are established in between farmland and water bodies. These strips filter runoff, trap sediments, nutrients, and pollutants, and protect water quality. Scenario 6 combines the structural benefits of terracing with the filtration capacity of vegetated strips. This integrated approach offers strong erosion control and enhanced water quality protection, especially on sloping lands. Scenario 8 integrates contour bund with filter strip, reduces both runoff and sediment loads. The bunds reduce slope length and velocity of runoff, while filter strips filter the water before it enters streams. Scenarios 6 and 7 are combinations of structural and non-structural BMP. Scenario 8 combine contour farming and filter strip merges here crops are aligned along contours with vegetated buffer zones. This combo reduces erosion and also treats surface runoff with low cost and eco-friendly conservation practice.

**Table 3 Scenarios**

| Scenario | Particulars |
|---|---|
| Scenario 1 | Base line |
| Scenario 2 | Bench terracing |
| Scenario 3 | Contour Bund |
| Scenario 4 | Contour farming |
| Scenario 5 | Filter strip |
| Scenario 6 | Bench terracing + Filter strip |
| Scenario 7 | Contour Bund+ Filter strip |
| Scenario 8 | Contour farming + Filter strip |

## III.RESULT

**Sensitive analysis:**

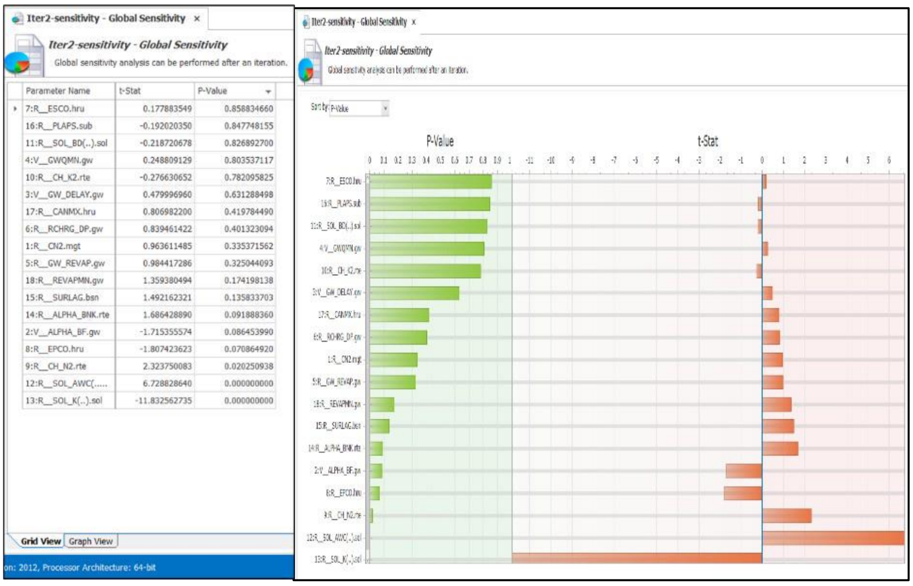
Sensitivity analysis is carried out to identify which parameters have the most significant impact. The objective was to identify the most influential parameters affecting the hydrological outputs of the SWAT model to ensure effective calibration and accurate simulation. The parameters selected for sensitive analysis are shown in the Table 4 below.

**Table 4 Parameters and its definition**

| Parameters and its definition |
|---|
| 1. **ALPHA_BF** – Base flow alpha factor |
| 2. **CN2** - SCS curve number for runoff |
| 3. **GW_DELAY** - Groundwater delay |
| 4. **GWQMN** - Threshold depth of water in shallow aquifer required for return flow |
| 5. **GW_REVAP** - Groundwater "revap" coefficient |
| 6. **REVAPMN** - Threshold depth of water for revap or percolation to occur |
| 7. **RCHRG_DP** - Deep aquifer percolation fraction |
| 8. **ESCO** – Soil evaporation compensation factor |
| 9. **EPCO** – Plant uptake compensation factor |
| 10. **CH_N2** – Manning's roughness coefficient for channels |
| 11. **CH_K2** – Effective hydraulic conductivity of channels |
| 12. **SOL_BD** – Soil bulk density |
| 13. **SOL_AWC**– Available water capacity of soil layer |
| 14. **SOL_K** – Saturated hydraulic conductivity of soil |
| 15. **ALPHA_BNK**– Baseflow alpha factor for bank storage |
| 16. **SURLAG**– Surface runoff lag time |

After the sensitive analysis based on t stat and p value it was found that the most sensitive parameters are SOL_AWC (Soil Available Water Capacity) with t-stat = -5.83, p-value = 0.000 SOL_K (Soil Hydraulic Conductivity) with t-stat = 11.82 and p-value = 0.000, and CH_N2 (Channel Manning's "n") with t-stat = 5.62, p-value = 0.000. EPCO (Plant Uptake Compensation) with t-stat = 1.88 and p-value = 0.070, ALPHA_BNK with t-stat = 1.69, p-value = 0.090 (Bank Storage

Recession) and ALPHA_BF (Baseflow Recession) with t-stat = -1.72, p-value = 0.086 were moderately sensitive. Other parameters were observed as least sensitive parameter. Fig 3 shows the result of sensitivity analysis green bar indicates the P-value and measures statistical significance of each parameter. Lower P-value (<0.05) indicate the parameter is highly sensitive and higher P-value indicates low sensitivity. The red bar indicates the t- stat. which measures the magnitude of sensitivity. Higher absolute t-stat value whether positive or negative indicates greater sensitivity, negative value suggests an inverse relationship when parameter increases output decreases. Positive values suggest direct relationships, increase in parameter increases the output. Lower absolute t-stat value indicates low sensitivity. From figure SOL_AWC, SOL_K and CH_N2 shows sensitivity most. EPCO, ALPHA_BNK and ALPHA_BF shows moderate sensitivity.




| Parameter Name | t-Stat | P-Value |
|---|---|---|
| 7:R__ESCO.hru | 0.177883549 | 0.858834660 |
| 16:R__PLAPS.sub | -0.192020350 | 0.847748155 |
| 11:R__SOL_BD(..).sol | -0.218720678 | 0.826892700 |
| 4:V__GWQMN.gw | 0.248809129 | 0.803537117 |
| 10:R__CH_K2.rte | -0.276630652 | 0.782095825 |
| 3:V__GW_DELAY.gw | 0.479996960 | 0.631288498 |
| 17:R__CANMX.hru | 0.806982200 | 0.419784490 |
| 6:R__RCHRG_DP.gw | 0.839461422 | 0.401323094 |
| 1:R__CN2.mgt | 0.963611485 | 0.335371562 |
| 5:R__GW_REVAP.gw | 0.984417286 | 0.325044093 |
| 18:R__REVAPMN.gw | 1.359380494 | 0.174198138 |
| 15:R__SURLAG.bsn | 1.492162321 | 0.135833703 |
| 14:R__ALPHA_BNK.rte | 1.686428890 | 0.091888360 |
| 2:V__ALPHA_BF.gw | -1.715355574 | 0.086453990 |
| 8:R__EPCO.hru | -1.807423623 | 0.070864920 |
| 9:R__CH_N2.rte | 2.323750083 | 0.020250938 |
| 12:R__SOL_AWC(..... | 6.728828640 | 0.000000000 |
| 13:R__SOL_K(..).sol | -11.832562735 | 0.000000000 |

*Fig 3 Tab showing the result of sensitivity analysis*

**Calibration and validation:**

Calibration and validation were done using the SWAT-CUP software using daily observed data for the year 2001-2023 from Kidangoor river gauge station. The result of model calibration for streamflow simulation using daily discharge data for the period 2001 -2014 and the result of model validation for period 2014-2017 are shown in the Fig 4 and Fig 5 respectively. The modelperformance was evaluated using the statistical indices Nash Sutcliffe efficiency and Coefficient of determination.300 simulations were carried out. During the calibration Nash Sutcliffe Efficiency (NSE) was observed as 0.55 and in validation NSE value 0.66. Santhi et al. (2001) reported that the NSE value greater than 0.50 are considered to be satisfactory for calibration and validation of SWAT model. This indicates that the performance rating of the calibrated and validated SWAT model for Meenachil river basin are satisfactory. The Coefficient of determination ($R^2$) value for the calibration and validation obtained was 0.71 and 0.89 respectively. The model performance was considered acceptable when the $R^2$ is greater than 0.6. (Santhi et al., 2001; Kang et al., 2006) [34, 18]. Therefore, the performance of the calibrated and validated SWAT model for Meenachil river basin was considered as satisfactory. The same sixteen parameters were used for calibration and validation process which was shown Table 3.

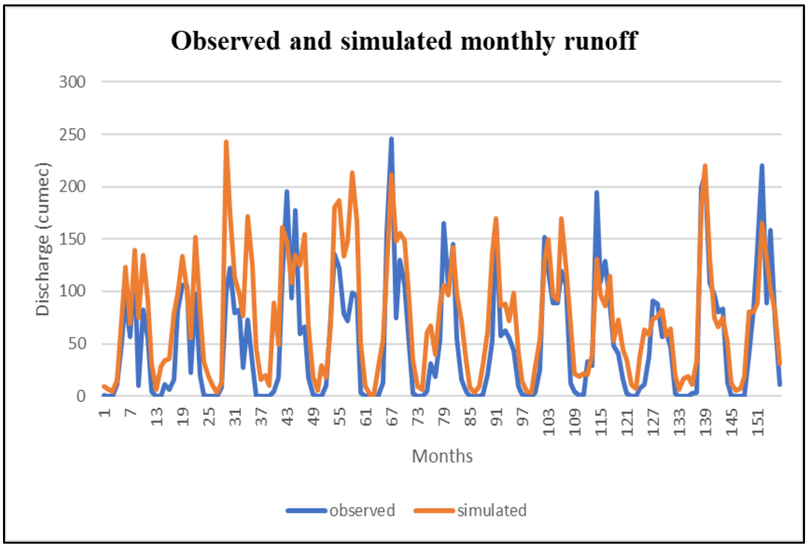



*Fig 4 Observed and simulated monthly runoff for the calibration period (2001-2014)*

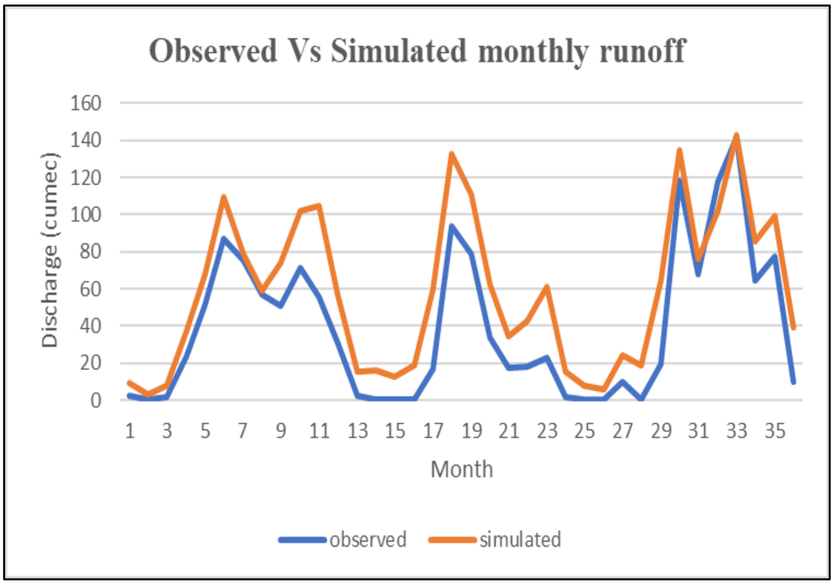



*Fig 5 Observed and simulated monthly runoff for the validation period (2014-2017)*

**Impact of best management practices for annual runoff reduction:**

The implementation of Best Management Practices (BMPs) has proven to be an effective strategy for mitigating surface runoff and enhancing watershed hydrology. BMPs were evaluated to know the impact on annual runoff reduction and the results showed that there was a significant decrease in annual runoff when BMPs were implemented. Over a 22-year period was analysed. The baseline (BL) scenario represents the runoff without any conservation measures. The BMPs were Bench Terracing (BT), Contour Bunding (CB), Contour Farming (CF), and Filter Strips (FS), and their combinations such as Bench Terracing and Filter Strip (BT+FS), Contour Bunding and Filter Strip (CB+FS), and Contour Farming and Filter Strips (CF+FS). The result of annual runoff over 22 years is shown in table 5 below.

**Table 5 Annual runoff under different Best Management Practices (BMPs) from 2002 to 2023**

| SUB | BL | BT | CB | CF | FS | BT+FS | CB+FS | CF+FS |
|---|---|---|---|---|---|---|---|---|
| 2002 | 90.05215 | 81.47688 | 81.47688 | 85.66624 | 89.3662 | 81.14681 | 81.14674 | 84.99889 |
| 2003 | 100.6303 | 90.43422 | 90.43422 | 95.29639 | 100.1855 | 90.17395 | 90.17383 | 94.8706 |
| 2004 | 137.3885 | 124.5728 | 124.5728 | 130.873 | 136.6283 | 124.2461 | 124.2459 | 130.1196 |
| 2005 | 134.5533 | 121.6583 | 121.6583 | 127.9142 | 133.915 | 121.3715 | 121.3714 | 127.3013 |
| 2006 | 159.732 | 145.2494 | 145.2494 | 152.4153 | 158.9638 | 144.9478 | 144.9477 | 151.6594 |
| 2007 | 112.0344 | 99.64656 | 99.64656 | 105.5884 | 111.2814 | 99.32017 | 99.32012 | 104.8691 |
| 2008 | 84.63705 | 74.82692 | 74.82691 | 79.44592 | 84.2339 | 74.63875 | 74.6387 | 79.06392 |
| 2009 | 84.21538 | 74.75463 | 74.75463 | 79.28187 | 83.54718 | 74.44878 | 74.44874 | 78.63996 |
| 2010 | 95.86437 | 84.68894 | 84.68894 | 89.90753 | 95.3508 | 84.44986 | 84.44983 | 89.42634 |
| 2011 | 71.86008 | 63.30857 | 63.30856 | 67.30142 | 71.56101 | 63.22869 | 63.22864 | 67.01925 |
| 2012 | 49.09485 | 42.78775 | 42.78775 | 45.72764 | 48.48028 | 42.42408 | 42.42401 | 45.14453 |
| 2013 | 94.40418 | 83.64625 | 83.64624 | 88.80222 | 93.70933 | 83.35221 | 83.35202 | 88.12945 |
| 2014 | 80.77489 | 71.59341 | 71.5934 | 75.92908 | 80.20881 | 71.3369 | 71.33684 | 75.39031 |
| 2015 | 57.38815 | 49.77085 | 49.77085 | 53.21853 | 56.99317 | 49.57375 | 49.57372 | 52.8508 |
| 2016 | 49.11942 | 43.3239 | 43.3239 | 45.96464 | 48.85805 | 43.19198 | 43.19188 | 45.72043 |
| 2017 | 73.04794 | 64.0511 | 64.0511 | 68.18524 | 72.605 | 63.83961 | 63.83956 | 67.77118 |
| 2018 | 93.93476 | 83.93623 | 83.93623 | 88.60078 | 93.53303 | 83.74093 | 83.7409 | 88.22876 |
| 2019 | 90.35869 | 80.38502 | 80.38502 | 85.07238 | 89.78936 | 80.1209 | 80.12086 | 84.53874 |
| 2020 | 91.20735 | 81.43206 | 81.43206 | 85.94725 | 90.97172 | 81.32979 | 81.32974 | 85.72929 |
| 2021 | 132.7859 | 118.028 | 118.028 | 124.8718 | 132.5916 | 117.9331 | 117.933 | 124.6917 |
| 2022 | 90.32999 | 79.59053 | 79.59053 | 84.50146 | 90.1325 | 79.50444 | 79.50444 | 84.30947 |
| 2023 | 74.22414 | 65.25876 | 65.25876 | 69.40204 | 73.8529 | 65.06887 | 65.06884 | 69.05478 |
| **Total** | **93.07445** | **82.92823** | **82.92823** | **87.72334** | **92.57995** | **82.6995** | **82.69943** | **87.25127** |

The annual runoff result showed a a clear pattern of reduction in runoff compared to the baseline when BMPs were implemented. For example, in the year 2006, the baseline runoff was 159.73 mm, it was reduced to 145.25 mm under BT and CB, 152.42 mm under CF, 158.96 mm under FS, 144.95 mm under BT+FS and CB+FS, and 151.66 mm under CF+FS. Among individual BMPs BT and CB reduced maximum runoff, compared to the baseline BT and CB reduced runoff by 10.14 mm. CF showed only a moderate reduction. From 93.074 CF was reduced to 87.723. A reduction of 5.35 mm was observed and the least reduction was seen in FS of a minor reduction of 0.49 mm. But when FS combined with other BMPs it showed maximum reduction. BT+FS and CB+FS achieved the maximum reduction of 10.37 mm. From BL, CF+FS was reduced to 87.251. Fig 6 shows graphical representation of this annual runoff reduction.

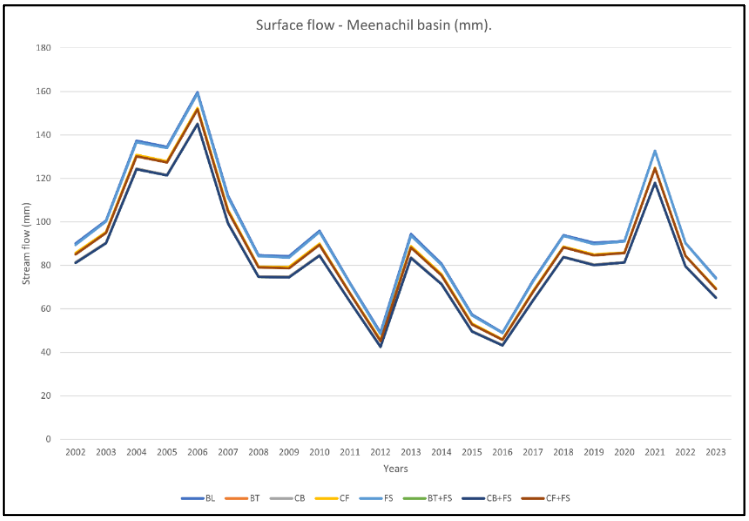



*Fig 6 Runoff trends under different BMPs from the year 2002 to 2023*

The graph shows the variation in annual surface flow across eight different scenarios. The x-axis represents the years and y-axis represents surface runoff in millimetres (mm). The most substantial differences in runoff between the baseline and BMP scenarios occur during high-rainfall years such as 2004, 2005, 2006, and 2021, indicating that BMPs play a crucial role in mitigating peak flows. 2006 shows the maximum runoff across all scenarios, with the baseline reaching nearly 160 mm. Results also indicate that BMPs are effective tools for runoff management in the Meenachil river basin. The structural BMPs (BT and CB) had significantly reduced the runoff, particularly in wetter years. While combining BT and CB with FS they perform even better since it slows down surface flow as well as enhances infiltration.

**Effectiveness of best management practices for annual runoff reduction:**

The average runoff reduction at subbasin level of Meenachil river basin before implementation of BMP and after implementation of BMP for different management scenarios are shown in the Table 7. Its graphical representation is shown in Fig 7. Effectiveness of conservation practices implemented was evaluated by comparing model simulations with no BMP and simulations with the BMP. Effectiveness of each practice (r) was derived from (Upadhye et al. 2021)

$$r = \frac{(y1-y2)}{y1} \times 100$$

Where, y1 and y2 reflect model outputs before and after implementation of the BMPs respectively.

**Table 7 Estimated average runoff and effectiveness of different BMPs for different subbasin**

| | Avg annual runoff after treatment (y)mm | | | | | | | | Effectivness%(Runoff) | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SUB | BL | BT | CB | CF | FS | BT+FS | CB+FS | CF+FS | BT | CB | CF | FS | BT+FS | CB+FS | CF+FS |
| 1 | 68.87 | 55.87 | 55.87 | 61.83 | 68.87 | 55.87 | 55.87 | 61.83 | 18.88 | 18.88 | 10.22 | 0.01 | 18.89 | 18.89 | 10.23 |
| 2 | 67.04 | 48.15 | 48.15 | 56.85 | 67.09 | 48.19 | 48.19 | 56.90 | 28.18 | 28.18 | 15.21 | -0.07 | 28.13 | 28.13 | 15.12 |
| 3 | 67.04 | 48.13 | 48.13 | 56.83 | 67.10 | 48.18 | 48.18 | 56.90 | 28.20 | 28.20 | 15.23 | -0.09 | 28.13 | 28.13 | 15.12 |
| 4 | 87.15 | 76.09 | 76.09 | 81.20 | 87.15 | 76.10 | 76.10 | 81.20 | 12.70 | 12.70 | 6.83 | 0.00 | 12.68 | 12.68 | 6.83 |
| 5 | 67.01 | 48.11 | 48.11 | 56.80 | 67.07 | 48.15 | 48.15 | 56.88 | 28.20 | 28.20 | 15.23 | -0.09 | 28.13 | 28.13 | 15.12 |
| 6 | 83.43 | 76.02 | 76.02 | 79.43 | 83.41 | 76.03 | 76.03 | 79.41 | 8.88 | 8.88 | 4.79 | 0.02 | 8.87 | 8.87 | 4.82 |
| 7 | 86.28 | 75.07 | 75.07 | 80.26 | 86.26 | 75.08 | 75.08 | 80.24 | 12.99 | 12.99 | 6.98 | 0.02 | 12.98 | 12.98 | 7.01 |
| 8 | 79.61 | 70.73 | 70.73 | 74.81 | 79.60 | 70.74 | 70.74 | 74.80 | 11.15 | 11.15 | 6.03 | 0.02 | 11.14 | 11.14 | 6.05 |
| 9 | 131.70 | 131.70 | 131.70 | 131.70 | 131.70 | 131.70 | 131.70 | 131.70 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 10 | 131.74 | 131.74 | 131.74 | 131.74 | 131.73 | 131.73 | 131.73 | 131.73 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 11 | 115.31 | 101.82 | 101.82 | 109.52 | 109.27 | 98.91 | 98.91 | 103.72 | 11.70 | 11.70 | 5.03 | 5.24 | 14.22 | 14.22 | 10.05 |
| 12 | 131.71 | 131.71 | 131.71 | 131.71 | 131.71 | 131.71 | 131.71 | 131.71 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| TOTAL | **93.07** | **82.93** | **82.93** | **87.72** | **92.58** | **82.70** | **82.70** | **87.25** | **13.41** | **13.41** | **7.13** | **0.42** | **13.60** | **13.60** | **7.53** |

The table shows detailed analysis of the average annual surface runoff (in mm) and the effectiveness of various BMPs in reducing runoff across the 12 sub-basins of the Meenachil River Basin. The baseline (BL), which is the scenario without implementing BMP average runoff value is 93.07 mm. Among the BMPs evaluated, Bench Terracing (BT) and Contour Bunding (CB) individually reduced runoff to 82.93 mm, achieving a runoff reduction effectiveness of 13.41%. Contour Farming (CF) alone has an average runoff reduction of 87.72 mm, reflecting a moderate effectiveness of 7.13%, while Filter Strips (FS) showed the least effectiveness, with an average runoff of 92.58 mm and a minimal reduction of only 0.42%. The results showed that among other individual treatments BT and CB has high runoff reduction efficiency. But when BMPs were combined high reduction efficiency was observed. Particularly combination of BT and FS and combination of CB and FS. The average runoff reduction was 82.69 mm, with highest effectiveness of 13.60%, indicating the synergistic benefit of integrating structural BMPs such as BT and CB with vegetative BMP FS. The CF+FS combination also improved runoff reduction to 87.25 mm, which was better than CF alone, with an effectiveness of 7.52%. Sub-basins 10, 11, and 12 showed no runoff reduction, indicating the possible limitations of BMP applicability or effectiveness in those regions due to topography, soil type, or land use conditions. Overall, the data clearly show that structural BMPs (BT and CB), particularly when combined with Filter Strips, provide the most effective strategy for managing surface runoff in the basin. Fig 7 shows the graphical representation of effectiveness of the BMPs. In the figure a bar chart visually representing the percentage reduction in surface runoff achieved by various Best Management Practices (BMPs) and their combinations is shown. Effectiveness here is defined as the percentage difference in runoff between baseline (BL) conditions and after implementing the BMPs. From this it is evident that Bench Terracing (BT) and Contour Bunding (CB) are the most effective individual BMPs, both showing a 13.41% reduction in surface runoff. Contour Farming (CF) shows moderate effectiveness with a 7.13% runoff reduction, Filter Strips (FS) is the least effective individual practice, with only a 0.42% reduction in runoff. This low value suggests that FS are beneficial for filtering sediments only their impact on reducing runoff is minimal when implemented alone. The most effective reduction was observed when BT or CB are combined with FS. Both combinations showed runoff reduction at 13.60%, slightly better than the individual implementation of BT or CB. This demonstrates that combining vegetative BMPs like FS with structural BMPs enhances the overall effectiveness. Lastly, the combination CF+FS shows a slightly improved effectiveness of 7.53%, just marginally higher than CF alone.

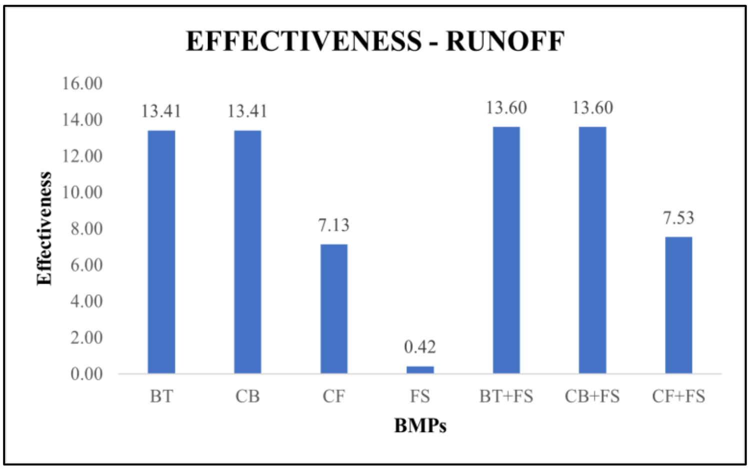



*Fig 7 Effectiveness of different treatments in runoff reduction*

## IV.DISCUSSION

The implementation of Best Management Practices (BMPs) in the Meenachil River Basin has demonstrated substantial potential in reducing surface runoff, enhancing infiltration, and supporting sustainable watershed management. The simulation results from the SWAT model revealed that both individual and combined BMPs had varying degrees of effectiveness depending on the characteristics of the sub-basins, such as topography, land use, and soil type. Among individual BMPs, bench terracing (BT) and contour bunding (CB) were the most effective, achieving a 13.41% reduction in runoff compared to the baseline scenario. These structural interventions altered the landscape to slow down surface water movement, allowing greater infiltration and minimizing the transport of sediments and nutrients. Contour farming (CF), a non-structural BMP, also showed moderate efficiency (7.13%) by aligning farming practices with the land's natural contours, thereby reducing runoff velocity and enhancing moisture retention in the root zone. However, filter strips (FS), despite their ecological benefits in trapping sediments and nutrients, contributed minimally to runoff reduction (0.42%) when implemented independently. This suggests that while FS are important for improving water quality, their impact on hydrological volume control is limited unless paired with other measures. The effectiveness of BMPs significantly improved when structural and vegetative measures were combined. Both BT+FS and CB+FS combinations exhibited the highest runoff reduction of 13.60%, indicating a synergistic benefit where structural interventions reduced the speed and volume of surface water while vegetative measures further enhanced infiltration and filtered the runoff. The CF+FS combination showed better performance (7.52%) than CF alone, underscoring the complementary effect of integrating vegetative buffers with land management practices. Temporal analysis across 22 years revealed that BMPs were especially critical during high-rainfall years such as 2004, 2006, and 2021. These findings highlight the role of BMPs in flood mitigation by reducing peak flow volumes. Spatially, certain sub-basins (10, 11, and 12) did not exhibit notable reductions, indicating that BMP effectiveness is also influenced by site specific factors like soil type, land slope, and land use dynamics. Therefore, targeted implementation of BMPs based on spatial prioritization can further enhance watershed-scale efficiency. The sensitivity analysis emphasized the importance of key parameters such as SOL_AWC, SOL_K, and CH_N2, which directly influence soil water holding capacity, infiltration rate, and channel roughness. The moderate NSE values (0.55 during calibration and 0.66 during validation) and high $R^2$ values (0.71 and 0.89, respectively) validate the model's reliability in replicating observed streamflow patterns and BMP impacts. Overall, the study demonstrates that effective runoff management in the Meenachil River Basin is achievable through a well-planned integration of structural and non-structural BMPs. The findings advocate for policy-level promotion of such combinations, especially in hilly and erosion-prone areas.

## V.CONCLUSION

The study successfully evaluated the impact of various Best Management Practices (BMPs) on reducing surface runoff in the Meenachil river basin using the SWAT model. The model performance during calibration and validation was satisfactory, indicating its reliability for hydrological simulation. Among the BMPs tested, bench terracing and contour bunding showed the highest effectiveness when implemented individually. However, the combination of structural BMPs with agricultural BMP like filter strips significantly enhanced runoff reduction, achieving up to 13.60% efficiency. The results highlight the importance of integrated management approaches for effective runoff control, especially in erosion-prone and high-rainfall areas. Additionally, the spatial variability in BMP performance underscores the need for site-specific implementation strategies. Overall, this study provides valuable insights for watershed planners and policymakers in adopting sustainable land and water management practices. Implementing suitable combinations of BMPs can play a crucial role in reducing soil erosion, improving water balance, and ensuring long-term watershed health in the Meenachil river basin.

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