



## **Assessment of climate change impacts on water balance using the swat model and conservation measures in agricultural watersheds: a comprehensive review**

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### **Abstract**

Climate change has become one of the most significant challenges affecting watershed hydrology, with profound implications for water resources, agricultural productivity, and ecosystem sustainability. Variations in temperature, precipitation patterns, and the frequency of extreme weather events are altering watershed water balance components, including surface runoff, evapotranspiration, groundwater recharge, soil moisture dynamics, and streamflow regimes. Agricultural watersheds are particularly susceptible to these changes due to their strong dependence on climatic conditions and water availability. This review synthesizes and critically evaluates recent studies employing the Soil and Water Assessment Tool (SWAT) to assess the impacts of climate change on watershed hydrology and to investigate the effectiveness of conservation measures in enhancing watershed resilience. Literature from diverse climatic regions was analyzed under different climate change scenarios, including Representative Concentration Pathways (RCPs) and Shared Socioeconomic Pathways (SSPs). The findings reveal that climate change is expected to increase hydrological variability, intensify droughts and floods, modify seasonal water availability, and influence groundwater recharge and streamflow patterns. Furthermore, conservation interventions such as best management practices (BMPs), conservation tillage, cover cropping, agroforestry systems, vegetative buffer strips, and water-harvesting structures have demonstrated considerable potential to mitigate adverse hydrological impacts and improve watershed sustainability. Despite these advancements, uncertainties related to climate projections, model parameterization, calibration procedures, input data quality, and long-term conservation effectiveness remain significant challenges. Emerging developments, including SWAT+, CMIP6-based climate projections, geospatial technologies, remote sensing, artificial intelligence, and nature-based solutions, offer promising opportunities for improving watershed assessment and supporting climate-resilient water resource management. This review provides a comprehensive synthesis of current knowledge and identifies future research directions for sustainable watershed planning under changing climatic conditions.

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## **Introduction**

Climate change has emerged as one of the most significant environmental challenges of the twenty-first century, profoundly affecting water resources, agricultural productivity, and ecosystem sustainability. Rising greenhouse gas concentrations have altered temperature and precipitation patterns, increasing the frequency and intensity of droughts, floods, and other extreme weather events. These changes directly influence watershed hydrology by modifying key water balance components such as surface runoff, evapotranspiration, groundwater recharge, soil moisture, and streamflow dynamics. Agricultural watersheds are particularly vulnerable because they depend heavily on reliable water availability for crop production and ecosystem functioning. Changes in rainfall patterns and increasing temperatures can intensify water scarcity, soil erosion, groundwater depletion, and hydrological extremes, thereby threatening agricultural sustainability and watershed resilience. Understanding the hydrological responses of watersheds to climate change is therefore essential for effective water resource management and long-term environmental planning. Agriculture is the largest consumer of freshwater resources globally, accounting for nearly 70% of total freshwater withdrawals. Consequently, climate-induced alterations in watershed hydrology can have substantial implications for irrigation water availability, crop productivity, food security, and rural livelihoods. Effective assessment of watershed water balance is therefore essential for identifying potential vulnerabilities and developing adaptive management strategies capable of sustaining agricultural production under future climate conditions. Hydrological models have become important tools for evaluating watershed responses under changing climatic conditions. Among these, the Soil and Water Assessment Tool (SWAT) is widely used due to its ability to simulate long-term hydrological processes, land-use dynamics, agricultural practices, and climate variability across diverse environmental settings. SWAT has been extensively applied to assess the impacts of climate change on runoff, evapotranspiration, groundwater recharge, sediment transport, and water quality. Although numerous studies have investigated climate change impacts on watershed hydrology using the SWAT model, comprehensive reviews integrating watershed water balance assessment, conservation measures, and emerging technologies such as SWAT+, CMIP6 climate projections, remote sensing, and artificial intelligence remain limited. In addition, existing studies often focus on individual hydrological processes or specific geographic regions, making it difficult to develop a holistic understanding of climate-resilient watershed management. This knowledge gap highlights the need for an updated synthesis of recent advances, challenges, and future opportunities in SWAT-based climate change assessment. This review provides a comprehensive synthesis of recent research on the application of SWAT and SWAT+ for assessing climate change impacts on watershed water balance in agricultural watersheds. It further evaluates the effectiveness of conservation measures and Best Management Practices (BMPs) in enhancing watershed resilience and supporting sustainable water resource management under future climate scenarios.

## **Literature review**

The Soil and Water Assessment Tool (SWAT) has emerged as one of the most widely applied hydrological models for assessing climate change impacts on watershed processes and water balance dynamics. Over the past two decades, SWAT has been extensively used to evaluate changes in runoff generation, streamflow patterns, evapotranspiration, groundwater recharge, sediment transport, and water availability under various climate change scenarios. These studies have provided valuable insights into watershed vulnerability and the effectiveness of adaptation strategies across diverse climatic and geographical regions. Research conducted across North

America, Asia, Europe, and Africa consistently indicates that climate change significantly influences watershed hydrology through alterations in temperature and precipitation patterns. These changes affect seasonal runoff regimes, groundwater recharge, evapotranspiration rates, streamflow dynamics, and overall water availability. Many studies have reported increased hydrological variability, greater flood risks, prolonged drought conditions, and growing uncertainty in water resource availability under future climate scenarios. Agricultural watersheds have been identified as particularly vulnerable to climate change because of their dependence on reliable water supplies for crop production. Changes in rainfall distribution, increasing temperatures, and rising evapotranspiration rates can significantly influence irrigation demand, groundwater resources, and agricultural productivity. Recent assessments utilizing advanced climate projections have further highlighted the increasing likelihood of hydrological extremes, including both droughts and flood events, across major agricultural regions. Beyond climate impact assessment, SWAT has been widely employed to evaluate conservation measures and Best Management Practices (BMPs). Studies have demonstrated that interventions such as conservation tillage, contour farming, vegetative filter strips, agroforestry systems, cover crops, farm ponds, and check dams can effectively reduce runoff and sediment losses, improve groundwater recharge, enhance soil moisture retention, and strengthen watershed resilience under changing climatic conditions. Overall, the available literature indicates that climate change is likely to intensify hydrological variability and alter key water balance components across agricultural watersheds worldwide. Surface runoff, evapotranspiration, groundwater recharge, and streamflow have emerged as the most climate-sensitive hydrological variables. Although SWAT has proven effective for assessing climate change impacts and evaluating conservation strategies, uncertainties associated with climate projections, model parameterization, calibration procedures, and input data quality remain important challenges. Future research should focus on integrating SWAT+, CMIP6 climate projections, remote sensing technologies, machine learning approaches, and nature-based solutions to improve prediction accuracy and support climate-resilient watershed management.

Table 1. Reported Climate Change Impacts on Watershed Water Balance

Hydrological Component	Expected Climate Change Impact	Implications
Surface Runoff	Increase in variability	Higher flood risk
Evapotranspiration	Increase	Greater water losses
Groundwater Recharge	Decline in many regions	Reduced groundwater availability
Soil Moisture	Decrease	Crop water stress
Streamflow	Altered seasonal patterns	Water management challenges

### Fundamentals of watershed water balance

Water balance is a fundamental hydrological concept that describes the movement, distribution, and storage of water within a watershed. It provides a quantitative framework for evaluating water availability, watershed sustainability, and the impacts of climate variability and land-use change. Water balance assessment is widely used to understand watershed responses to environmental changes and to support effective water resource management.

### **Concept of Water Balance**

The water balance of a watershed is based on the principle of mass conservation; whereby total water inputs are equal to the sum of outputs and changes in storage. It can be expressed as:

$$P = ET + Q + \Delta S$$

where  $P$  represents precipitation,  $ET$  denotes evapotranspiration,  $Q$  refers to runoff or streamflow, and  $\Delta S$  indicates changes in water storage. Precipitation serves as the primary input, while water is lost through evapotranspiration and runoff, with the remaining portion contributing to soil moisture and groundwater storage. Understanding these interactions is essential for assessing the hydrological impacts of climate change.

### **Major Water Balance Components**

The principal components of watershed water balance include surface runoff, groundwater recharge, baseflow, soil moisture, and evapotranspiration. Surface runoff influences streamflow generation and flood potential, whereas groundwater recharge sustains aquifer storage and long-term water availability. Baseflow maintains river discharge during dry periods and supports aquatic ecosystems. Soil moisture acts as a key link between hydrological processes and agricultural productivity, while evapotranspiration represents one of the largest pathways of water loss from a watershed. Changes in temperature and precipitation can significantly alter these components, affecting overall watershed functioning.

### **Factors Influencing Watershed Water Balance**

Watershed water balance is controlled by climatic, physiographic, and anthropogenic factors. Climate variables such as precipitation and temperature directly regulate runoff, groundwater recharge, and evapotranspiration. Land-use and land-cover characteristics influence infiltration and water retention, while soil properties determine water storage and movement within the soil profile. Topography affects runoff generation and erosion processes through variations in slope and elevation. In addition, agricultural practices, including irrigation, conservation tillage, crop rotation, and other Best Management Practices (BMPs), can significantly modify hydrological responses and improve watershed resilience. The interaction of these factors ultimately determines the magnitude and distribution of water balance components under changing climatic conditions.

### **Climate change and hydrological responses**

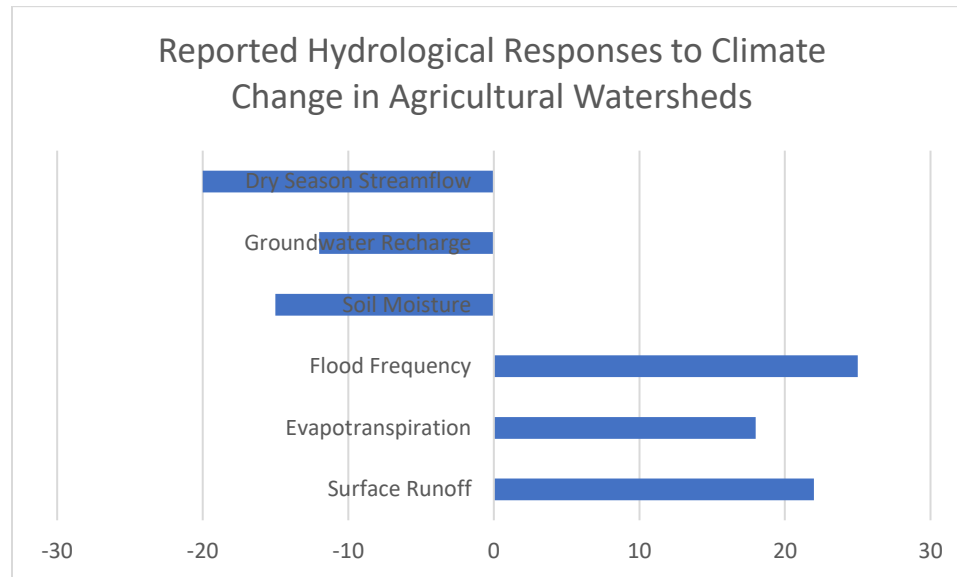
Climate change is one of the most significant drivers of hydrological change, affecting water availability, watershed processes, and ecosystem sustainability worldwide. Increasing greenhouse gas (GHG) concentrations resulting from fossil fuel combustion, industrialization, deforestation, and land-use changes have accelerated global warming, leading to alterations in precipitation patterns, temperature regimes, and the frequency of extreme weather events. These changes directly influence watershed hydrology and the distribution of water resources.

Future climate conditions are commonly assessed using Global Climate Models (GCMs) developed under the Coupled Model Intercomparison Projects (CMIP5 and CMIP6). Climate projections are represented through Representative Concentration Pathways (RCPs) and, more recently, Shared Socioeconomic Pathways (SSPs), which provide scenarios for evaluating potential climate impacts on hydrological systems and water resources.

Climate-induced changes in temperature and precipitation significantly affect watershed water balance components. Increased rainfall intensity often results in higher surface runoff, flooding, soil erosion, and sediment transport, whereas prolonged dry periods contribute to droughts and water scarcity. Rising temperatures enhance evapotranspiration rates, reduce soil moisture availability, and alter groundwater recharge dynamics. Consequently, streamflow patterns,

seasonal water availability, and groundwater resources are increasingly vulnerable to climatic variability and change.

Agricultural watersheds are particularly susceptible to these impacts because of their dependence on reliable water supplies for crop production. Higher temperatures and altered rainfall patterns increase irrigation demand and crop water requirements, while extreme weather events can reduce agricultural productivity through water stress, erosion, and nutrient losses. These challenges highlight the importance of climate-resilient watershed management strategies, conservation practices, and adaptive water resource planning to ensure long-term agricultural and environmental sustainability.



*Figure 1. Generalized hydrological responses reported in climate change impact studies conducted using SWAT and related hydrological models.*

Values represent generalized ranges synthesized from published SWAT-based climate change assessment studies and are presented for comparative illustration purposes.

### SWAT Model

The Soil and Water Assessment Tool (SWAT) is a physically based, semi-distributed hydrological model developed by the United States Department of Agriculture–Agricultural Research Service (USDA-ARS) to evaluate the impacts of climate variability, land-use change, and management practices on watershed hydrology. Owing to its capability to simulate long-term watershed processes under diverse environmental conditions, SWAT has become one of the most widely used models for climate change impact assessment and watershed management.

SWAT represents watersheds through sub-basins and Hydrologic Response Units (HRUs), which are unique combinations of land use, soil type, and slope characteristics. Using climatic inputs such as precipitation, temperature, solar radiation, humidity, and wind speed, the model simulates key hydrological processes including surface runoff, infiltration, evapotranspiration, groundwater recharge, lateral flow, and streamflow generation.

The hydrological simulations are based on the watershed water balance equation:

$$SW_t = SW_0 + \sum (R^{\text{day}} - Q^{\text{surf}} - ET - W^{\text{seep}} - Q^{\text{gw}})$$

where  $SW_i$  is the final soil water content,  $SW_o$  is the initial soil water content,  $R_{day}$  represents daily precipitation,  $Q_{surf}$  denotes surface runoff,  $ET$  refers to evapotranspiration,  $W_{seep}$  is percolation below the root zone, and  $Q_{gw}$  indicates groundwater return flow. This equation forms the basis of continuous watershed water balance assessment.

Reliable SWAT simulations require high-quality spatial and temporal datasets, including Digital Elevation Models (DEMs), soil data, land-use information, and meteorological records. Model performance is commonly evaluated through calibration and validation procedures using statistical indicators such as Nash–Sutcliffe Efficiency (NSE), Coefficient of Determination ( $R^2$ ), Percent Bias (PBIAS), and Root Mean Square Error (RMSE). Recent advancements, particularly the development of SWAT+, have improved model flexibility and spatial representation, enhancing its applicability in climate change and watershed management studies.

### **Applications of SWAT in Climate Change Assessment**

SWAT has been extensively applied worldwide to evaluate the impacts of climate change on watershed hydrology and water resources. Studies conducted across North America, Europe, Asia, and Africa consistently demonstrate that changing temperature and precipitation patterns influence streamflow, surface runoff, groundwater recharge, evapotranspiration, and overall water availability.

Climate change assessments based on Representative Concentration Pathways (RCPs) and Shared Socioeconomic Pathways (SSPs) indicate increasing hydrological variability, greater flood and drought risks, altered seasonal runoff patterns, and growing pressure on agricultural water resources. Among the various water balance components, surface runoff, evapotranspiration, groundwater recharge, and streamflow have been identified as the most sensitive to future climate conditions.

One of the major strengths of SWAT is its ability to evaluate adaptation and conservation strategies under projected climate scenarios. The model has been widely used to assess the effectiveness of Best Management Practices (BMPs), land-use modifications, and watershed conservation measures aimed at reducing runoff, enhancing groundwater recharge, improving soil moisture retention, and strengthening climate resilience.

Despite its widespread application, uncertainties associated with climate projections, model parameterization, calibration procedures, and input data quality remain important challenges. Consequently, recent studies increasingly integrate SWAT+, CMIP6 climate projections, remote sensing technologies, geographic information systems (GIS), and machine learning approaches to improve prediction accuracy and support sustainable watershed management under changing climatic conditions.

### **Conservation measures in agricultural watersheds**

Agricultural watersheds are increasingly vulnerable to climate change impacts, including altered precipitation patterns, prolonged droughts, extreme rainfall events, soil erosion, groundwater depletion, and declining agricultural productivity. To address these challenges, conservation measures have become essential for enhancing watershed resilience and ensuring sustainable water resource management. These interventions help maintain watershed hydrological balance by reducing runoff, improving infiltration, conserving soil moisture, minimizing sediment losses, and enhancing groundwater recharge.

Conservation measures can be broadly categorized into structural, vegetative, and soil-water management practices. Structural interventions such as check dams, farm ponds, terracing, and contour bunding are designed to regulate water movement, reduce erosion, and increase water

storage within watersheds. These measures are particularly effective in improving groundwater recharge and mitigating flood risks in water-stressed regions.

Vegetative conservation practices, including cover crops, buffer strips, agroforestry systems, and grass waterways, enhance watershed stability by protecting soil surfaces, improving infiltration, reducing sediment transport, and increasing ecosystem resilience. In addition to their hydrological benefits, these practices contribute to biodiversity conservation and carbon sequestration.

Soil and water conservation measures such as conservation tillage, mulching, and crop rotation improve soil structure, increase water-holding capacity, reduce evaporation losses, and enhance overall agricultural sustainability. These practices play a significant role in improving soil health and strengthening the adaptive capacity of agricultural systems under changing climatic conditions.

Best Management Practices (BMPs) integrate structural, vegetative, and management interventions to achieve sustainable watershed development. The SWAT model has been widely used to evaluate the effectiveness of BMPs by simulating their impacts on runoff, sediment yield, nutrient transport, water quality, and groundwater recharge. Numerous studies have demonstrated that BMP implementation can significantly reduce hydrological vulnerabilities, improve water resource conservation, and enhance watershed resilience to climate change. Consequently, the integration of conservation measures with SWAT-based assessment has emerged as an effective approach for climate-resilient watershed planning and sustainable agricultural development.

### **Effectiveness of Conservation Measures Under Climate Change**

Climate change is expected to intensify hydrological extremes through increased rainfall variability, prolonged droughts, and more frequent flood events, posing significant challenges to agricultural watersheds. Conservation measures have emerged as effective adaptation strategies for mitigating these impacts and improving watershed resilience. Evidence from field investigations and SWAT-based studies indicates that conservation interventions can substantially improve watershed hydrology and enhance climate adaptation capacity.




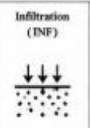
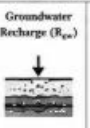
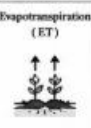


















The effectiveness of conservation measures is primarily reflected in their ability to reduce surface runoff, increase groundwater recharge, improve soil moisture retention, decrease sediment yield, and enhance water-use efficiency. Structural practices such as check dams, farm ponds, contour bunding, and terracing reduce runoff velocity and promote infiltration, thereby lowering flood risks and improving groundwater replenishment. Similarly, vegetative measures including cover crops, buffer strips, grass waterways, and agroforestry systems help stabilize soils, reduce erosion, and improve watershed water retention.

Conservation practices also play a critical role in maintaining soil moisture under increasing temperatures and evapotranspiration rates. Measures such as mulching, conservation tillage, and cover cropping enhance soil water-holding capacity, reduce evaporation losses, and improve drought resilience. In addition, integrated conservation strategies significantly reduce sediment transport, thereby protecting soil fertility, maintaining water quality, and minimizing reservoir sedimentation.

Numerous SWAT-based assessments have demonstrated that the combined implementation of structural, vegetative, and management-based interventions provides greater hydrological benefits than individual practices alone. These integrated approaches improve water-use efficiency, support sustainable agricultural production, and strengthen watershed resilience under future climate scenarios. Consequently, conservation measures are increasingly recognized as essential components of climate-resilient watershed management and long-term water resource sustainability.

## Conservation Measures and Their Hydrological Benefits

### Enhancing Watershed Resilience and Water Balance under Climate Change

Type of Measure	Conservation Measures (Examples)	Mechanism / How It Works	Hydrological Benefits						Key Outcomes
			Surface Runoff ( $Q_{surf}$ )	Infiltration (INF)	Groundwater Recharge ( $R_{gw}$ )	Evapotranspiration (ET)	Soil Moisture (SM)	Streamflow (Q)	
 Structural Measures	<ul style="list-style-type: none"> <li>Check Dams</li> <li>Farm Ponds</li> <li>Percolation Tanks</li> <li>Contour Bunds</li> <li>Terracing</li> <li>Gully Plugs</li> <li>Retention Structures</li> </ul>	<ul style="list-style-type: none"> <li>Slow down surface runoff</li> <li>Impound and store water</li> <li>Enhance infiltration and percolation</li> <li>Reduce flow velocity and peak discharge</li> <li>Trap sediment and reduce soil erosion</li> </ul> 							<ul style="list-style-type: none"> <li>Reduced flood risk</li> <li>Increased water storage</li> <li>Enhanced recharge</li> <li>Reduced soil erosion</li> </ul>
 Vegetative / Agro-Ecological Measures	<ul style="list-style-type: none"> <li>Afforestation / Reforestation</li> <li>Riparian Buffer Strips</li> <li>Agroforestry</li> <li>Cover Crops</li> <li>Grassed Waterways</li> <li>Windbreaks</li> </ul>	<ul style="list-style-type: none"> <li>Intercept rainfall</li> <li>Increase root depth and soil porosity</li> <li>Improve soil structure and stability</li> <li>Reduce overland flow and soil loss</li> <li>Enhance evapotranspiration regulation</li> </ul> 							<ul style="list-style-type: none"> <li>Improved ecosystem health</li> <li>Enhanced baseflow</li> <li>Better water quality</li> <li>Increased resilience to drought</li> </ul>
 Soil & Water Management Measures	<ul style="list-style-type: none"> <li>Conservation Tillage</li> <li>Mulching</li> <li>Contour Farming</li> <li>Strip Cropping</li> <li>Crop Rotation</li> <li>Organic Matter Addition</li> </ul>	<ul style="list-style-type: none"> <li>Improve soil physical properties</li> <li>Increase water holding capacity</li> <li>Reduce runoff and erosion</li> <li>Enhance soil organic carbon and infiltration</li> </ul> 							<ul style="list-style-type: none"> <li>Improved soil health</li> <li>Higher water use efficiency</li> <li>Sustainable crop productivity</li> </ul>

**Impact Scale (Relative)**


↑↑ Significant Increase      ↓ Moderate Decrease

↑ Moderate Increase      ↓↓ Significant Decrease

— No Significant Change

**Notes:**

- Effects may vary with climate, soil type, land use, topography, and scale.
- Integrated use of multiple measures provides synergistic benefits for watershed resilience and water security.

 Climate Input


 Hydrological Response

Figure 2. Hydrological benefits of structural, vegetative, and soil-water conservation measures in agricultural watersheds under climate change conditions.

### Research gaps and challenges

Despite the widespread application of the SWAT model in climate change impact assessment, several challenges continue to limit the accuracy and reliability of watershed simulations. One of the major constraints is the limited availability and quality of hydrological, meteorological, soil, and land-use datasets, particularly in developing regions. Inadequate monitoring networks and incomplete datasets often introduce significant uncertainties into model calibration and prediction.

Model-related limitations also remain important. Although SWAT effectively simulates long-term watershed processes, its representation of extreme hydrological events, complex groundwater interactions, and spatial heterogeneity may be insufficient in some environments. Uncertainties associated with parameterization, calibration procedures, climate projections, and downscaling techniques further influence simulation outcomes.

Another challenge involves the evaluation of conservation measures under changing climatic conditions. Long-term monitoring data are often unavailable, making it difficult to assess the sustained effectiveness of adaptation strategies. Moreover, socioeconomic factors such as financial feasibility, policy support, stakeholder participation, and adoption barriers are frequently overlooked in hydrological assessments.

Recent advances in remote sensing, machine learning, artificial intelligence, and digital twin technologies provide opportunities to address these limitations. However, their integration into watershed-scale climate change studies remains limited, highlighting important research gaps in climate-resilient watershed management.

## Conclusions

Climate change is increasingly influencing watershed hydrology by altering temperature regimes, precipitation patterns, evapotranspiration, and the occurrence of extreme weather events. These changes significantly affect key water balance components, including surface runoff, groundwater recharge, soil moisture, and streamflow, thereby impacting water availability and agricultural sustainability. Agricultural watersheds are particularly vulnerable due to their dependence on reliable water resources for crop production and ecosystem functioning.

This review demonstrates that the Soil and Water Assessment Tool (SWAT) remains one of the most effective hydrological models for assessing climate change impacts on watershed systems. Its capability to integrate climatic, land-use, soil, and management data enables comprehensive evaluation of watershed responses under current and future climate scenarios. Findings from studies conducted across different regions consistently indicate increasing hydrological variability, greater flood and drought risks, and growing pressure on water resources under projected climate conditions.

The review further highlights the importance of conservation measures and Best Management Practices (BMPs) in enhancing watershed resilience. Structural, vegetative, and soil conservation interventions have shown considerable potential to reduce runoff, improve groundwater recharge, conserve soil moisture, control sediment losses, and enhance water-use efficiency. SWAT-based assessments confirm that integrated conservation strategies can significantly support climate adaptation and sustainable watershed management.

Despite these advancements, uncertainties related to climate projections, data availability, model parameterization, and long-term evaluation of conservation measures remain important challenges. Future research should focus on integrating SWAT+, CMIP6 climate projections, remote sensing, artificial intelligence, nature-based solutions, and multi-model approaches to improve prediction accuracy and decision support. Overall, the combination of advanced hydrological modeling and effective conservation planning will be essential for strengthening water security, enhancing agricultural resilience, and promoting sustainable watershed management under a changing climate.

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