International Journal of Research in Engineering and Science (IJRES)
ISSN (Online): 2320-9364, ISSN (Print): 2320-9356
www.ijres.org Volume 11 Issue 10 ǁ October 2023 ǁ PP. 173-182

Water Resource Planning and Management Using WEAP and SWAT Models- A Review

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Abstract
With growing evidence in the vulnerability of river basins to water availability due to the potential effects of climate change, managers of natural resources need tools with which can be used to predict and therefore respond to changes in those resources. Hydrologic models are the simplified conceptual representation of a part of the hydrologic cycle, and are primarily used for hydrologic prediction and understanding of the water resources systems processes. A review of some current studies that assess the impacts of climate change using Water Evaluation And Planning (WEAP) and Soil and Water Assessment Tool (SWAT) was undertaken. There is less agreement on the magnitude of change of climatic variables. Still, several studies have shown that climate change will impact the availability and demand for water resources and is likely to affect nearly every aspect of human well-being, from agricultural productivity and energy use to flood control, municipal and industrial water supply to wetlands and wildlife management. Challenges associated with earth observation and in-situ climatic data certainly represent existing research and knowledge gaps in climate change impact analysis.
Keywords: *Climate change Impact, Vulnerability, Models, Prediction, Water resource management*

Date of Submission: 05-10-2023 Date of acceptance: 19-10-2023

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1. INTRODUCTION

The IPCC (Intergovernmental Panel on Climate Change) in 2013 drew a clear distinction between weather and climate. Weather, according to their definition, relates to the atmospheric conditions at a specific place and time, encompassing elements such as precipitation, temperature, pressure, humidity, wind, and special phenomena like thunderstorms, dust storms, and tornadoes. In contrast, climate refers to the long-term average of weather patterns and associated statistics, including frequency, magnitude, and trends, typically spanning 30 years or more [22]. Climate change, as defined, involves alterations in the state of the climate system or deviations from regional climatic norms. These changes are identified through the analysis of long-term measurements using methods such as statistical tests. Climate change persists over extended periods, typically lasting decades or longer, and it can result from natural processes as well as human activities. These factors, both natural and anthropogenic, influence the Earth's energy budget and drive the shifts observed in our climate system [22].

Climate models, which build upon the principles of weather forecasting, are designed for long-term predictions of how regional climate conditions will evolve over extended periods. These models rely on complex mathematical equations fueled by extensive data to simulate energy and water dynamics in the climate system. They provide a framework for understanding climate processes, incorporating improved observations, and projecting future climate changes. There are three main types of climate models: Energy Balance Models (EBMs) forecast climate changes based on Earth's energy budget, Intermediate Complexity Models (ICMs) offer a less detailed but comprehensive view of climate patterns, and General Circulation Models (GCMs) are the most precise and complex, providing in-depth insights into climate systems. GCMs, widely used today, encompass information about atmospheric chemistry, land types, the carbon cycle, ocean circulation, and glacial characteristics [40].

Numerous literature sources are available, comprising a wealth of reports that extensively document the utilization of hydrologic models to evaluate the potential impacts of climate change on various water resource concerns. The objective of this paper is to examine a selection of these hydrology and water resources modelling studies, specifically focusing on their application in simulating the consequences of climate change, while also highlighting areas where further research is required.

II. HYDROLOGIC MODELS

Hydrologic models serve the key purpose of studying the functioning of hydrologic systems and predicting water distribution using the continuity equation ($Q = P - ET \pm \Delta S$) [34]. These models are classified into physical and mathematical types based on their description of physical processes and spatial catchment representation [16]. The choice of model depends on factors like its intended application, structure, spatial and temporal scales. Many hydrological models have been employed to assess climate change impacts on watersheds, including WEAP and SWAT models, reflecting the latest advancements in hydrological modelling.

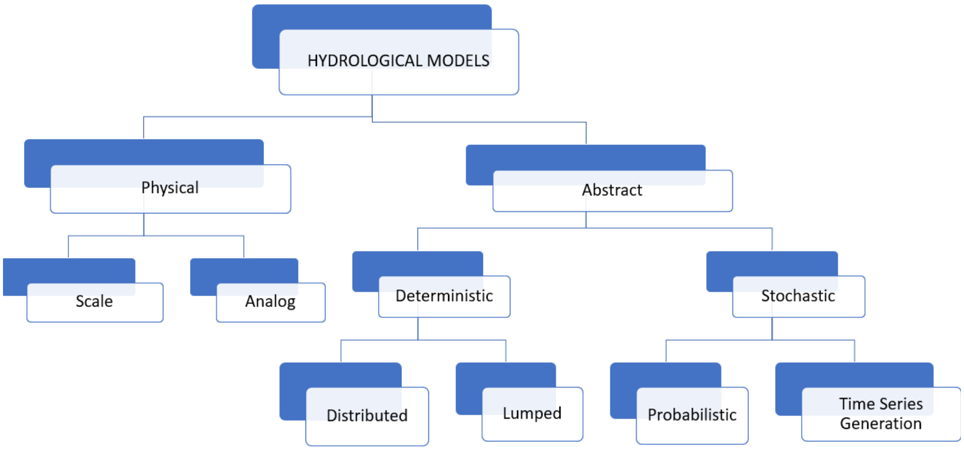

Figure 2: Classification of hydrological models [16]

III. SIMULATIONS USING WEAP AND SWAT MODELS UNDER DIFFERENT SCENARIOS

Climate change has substantial impacts on water resources, affecting supply, demand, agriculture, reservoir management, and decision support systems (Ashofteh et al., 2017; Duan et al., 2017; Ahmadaali et al., 2018; Aryal et al., 2018; Bajracharya et al., 2018; Bhave et al., 2018; Khalil et al., 2018; Shiferaw et al., 2018). To assess these impacts alongside population growth, scenarios are developed based on IPCC's Representative Concentration Pathways (RCPs) and national policies (Blanco-Gutiérrez et al., 2011; Hamlat et al., 2012; Pervez and Henebry, 2015; Abbas et al., 2016a; Adhikari and Nejadhashemi, 2016; Johannsen et al., 2016; Chattopadhyay et al., 2017; Islam et al., 2017; Pham et al., 2017; Spalding-Fecher et al., 2017; Stefanidis et al., 2018; Tiwari et al., 2018).

Simulating a catchment's hydrological response under different scenarios involves two steps: calibration and validation of the hydrologic model. Calibration tunes model parameters to match observed data, while validation assesses the model's performance in replicating hydrological components.

3.1 WEAP MODEL

WEAP is a data-driven system designed for simulating watersheds using a user-friendly graphical interface. Its platform allows for a comprehensive assessment of multiple watershed factors, including climate, hydrology, land use, irrigation infrastructure, water allocation, and management priorities.

Within the WEAP model, there are three options for simulating watershed hydrological processes: Soil Moisture, Rainfall-Runoff, and the Simplified Coefficient Approach method [44]. Figure 2 illustrates the conceptual framework of the WEAP model.

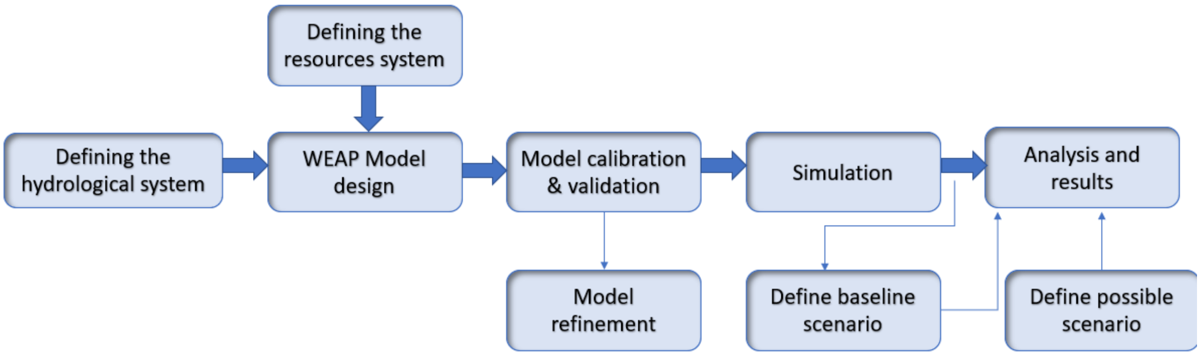

Figure. 2: Conceptual framework of the WEAP model and its setup [35]

3.1.1 Forecasting the impacts of climate change on the management of water resources through the utilization of the WEAP model

Mounir et al. (2011) employed the WEAP model to enhance their understanding of the hydrology in the Niger River Basin and how water resources could be efficiently allocated to meet various competing demands, both present and future. This basin, located in the Niger Republic, encompasses diverse ecosystems such as biosphere reserves and wildlife parks, supports substantial livestock and agriculture, and is witnessing industrial growth. Managing water resources in this region is challenging due to a multitude of socio-cultural, ecological, and economic factors.

Conversely, Blanco-Gtiérrez et al. (2011) utilized the WEAP model to replicate the hydrological processes within the catchment area and represent the broader water system operations in the Middle Guadiana basin in Spain. They also considered the behavior of farmers by employing a multi-scale economic optimization model to assess how different water policies might impact large-scale irrigation systems under both normal and dry climate conditions. The combination of hydrology and economic models in this study involved two approaches: one was empirical, where irrigation demand nodes were replicated, and the same scenarios were run in both models, while the other was technical, involving the use of an automated wrapper interface to facilitate data exchange between the two models. The research demonstrated that when economic and hydrology models are integrated, they become more accurate in predicting the behavior of farmers and water systems, showcasing the potential of integrated tools to mirror the complexities of real-world water systems.

Additionally, Comair et al. (2012) conducted a study on water resources management in the Jordan River Basin, focusing on the vulnerability of Lower Jordan River water resources to changing climate patterns and increasing water demands as analyzed by the WEAP model. The findings indicated that all aquifers supplying water to the city of Amman are at risk of depletion in the coming decades. Meanwhile, Hamlat et al. (2013) employed the WEAP model to simulate scenarios for water resources management in watersheds in western Algeria. The study's results affirmed that the WEAP software provides a robust foundation for aiding planners in developing recommendations for future water resource management by identifying key areas for action. Bhave et al. (2014) conducted a study that involved using the WEAP model to evaluate the potential consequences of climate change on water resources. They also assessed adaptation options that stakeholders prioritized to address these adaptation needs. The model emphasized the benefits of a comparative assessment of various adaptation options. To summarize, a comprehensive approach that includes the participation of stakeholders, scenario analysis, modeling techniques, and multi-model projections can be valuable for making decisions about adapting to climate change in the presence of uncertainties. In a different study, Esteve et al. (2015) employed the WEAP model to create a hydro-economic model aimed at evaluating the impacts of climate change and adaptation strategies in irrigated agriculture. WEAP's capability to represent the physical and spatial aspects of water resources and climate is crucial for assessing climate change impacts, particularly in terms of managing the water supply side.

Furthermore, Johannsen et al. (2016) utilized the WEAP model in the Middle Draâ valley in Morocco to determine water demand and supply. This analysis included various socioeconomic and land-use scenarios under a single foundational climate change scenario. A climate scenario indicates a significant reduction in available water resources by 2029, while all socioeconomic scenarios project an increase in water demand. Spalding-Fecher et al. (2017) employed the WEAP model to examine and create integrated water and power scenarios for the Zambezi River Basin. Their goal was to involve stakeholders and provide information to decision-makers, assessing potential climate change impacts on water availability and energy security in the basin and the Southern African Power Pool. Results revealed a critical need to consider both climate change and upstream development demands when expanding existing hydropower stations or building new ones. This integration is essential for feasibility studies and investment decisions, including potential adaptations in design and operation.

Leong and Lai (2017) utilized a straightforward integrated water resources management model developed based on WEAP to demonstrate its effectiveness in managing complex water systems. They applied this approach to a specific catchment area, the Langat River basin in Malaysia. The model simulated various future scenarios, aiding in the evaluation of the current and future water management system in the Langat River Basin and facilitating decision-making by providing an integrated management planning network for resolving water allocation conflicts. In the case of the Klela basin in Kenya, Touré et al. (2017) used WEAP to assess the impact of climate change and population growth on groundwater resources. Their findings indicated that groundwater storage was decreasing primarily due to the effects of climate change and human activities.

Gao et al. (2017) applied the WEAP model for a Strategic Environmental Assessment (SEA) to measure the impact of implementing a proposed plan on the local water resource system in arid and semi-arid areas of China. The model made it easy to simulate and compare the results of different water utilization scenarios, demonstrating its usefulness for rapid water utilization assessment as part of SEA conclusions. Duque and Vázquez (2017) worked on monthly water balance modeling for an irrigation project in a semi-arid region of southern-central Chile, using historical data and climate change predictions. They utilized WEAP21 as their modeling tool, considering historical records and climate forecasts indicating a potential temperature increase of around +1.1°C and a maximum precipitation reduction of 20.7%. Hydrological modeling indicates a potential maximum decrease of 49.7% in mean annual streamflow, along with reduced streamflow peak frequency and magnitude. The conclusion drawn is that the irrigation project is likely to be significantly impacted concerning water availability and crop water consumption due to climate change uncertainties. This is primarily because of expected decreases in rainfall and potential increases in temperature and evapotranspiration.

In a study by Khalil et al. (2018), the WEAP model was employed to assess the current water supply and demand dynamics in the Mae Klong Basin, Thailand. They created six different scenarios to assess the basin's response to increasing demands under two Special Report on Emissions Scenarios (SRES): A2 and B2. The results indicated that the basin's water resources are sufficient to meet current needs during the wet season. However, under the A2 scenario, more water shortages were observed compared to the B2 scenario. The study suggested potential water scarcity issues in the basin, particularly in scenario five, where transferring water to adjoining areas may be challenging. The WEAP model implemented in the basin can be a valuable tool for decision-makers in effective water resource management.

Ahmadaali et al. (2018) used the WEAP21 model to assess environmental and agricultural sustainability indices influenced by climate change and water management strategies in the Zarrinehrud and Siminehrud River basins. They considered three future emission scenarios (A2, A1B, and B1) for the period 2015-2040 and incorporated five water management scenarios to evaluate the basin's response to these future emission scenarios. Results indicated that the highest sustainability indices were associated with the scenario that combined changes in crop patterns with improved irrigation efficiency under the B1 emission scenario (B1S4). Bhave et al. (2018) developed an iterative Multi-Decision-Making under Uncertainty (M-DMUU) approach, which included scenario generation, stakeholder engagement, and water resources modeling as part of their study. The researchers applied this approach to assess the resilience of adaptation strategies to uncertainties in climate and socioeconomic factors in the Cauvery River Basin, located in Karnataka, India. They utilized the WEAP model, which was satisfactorily calibrated and validated using observed streamflow data, with a focus on monthly and annual flows at downstream gauging stations. The simulations covered the period from 2021 to 2055, considering reasonable changes in Indian Summer Monsoon precipitation and water demand. The study demonstrated that changes in both climate and socioeconomic variables significantly impact the performance of the future water resource system. The iterative DMUU approach proved valuable as it allowed the analysis to adapt to the decision context and stakeholder needs, enhancing stakeholder engagement and knowledge co-production.

In contrast, Al-Zubari et al. (2018) assessed the vulnerability of municipal water management systems to climate change impacts in the Kingdom of Bahrain. They developed a model using the WEAP software, which was calibrated and validated using historical data from 2000 to 2012. The model evaluated the performance of the municipal water sector, including water demand and associated costs, both with and without climate change scenarios for the period 2012 to 2030. The impact of climate change on the municipal water system was quantified by comparing two scenarios in terms of three key cost indicators: financial (production, conveyance, and distribution costs), economic (natural gas consumption by desalination plants), and environmental (CO2 emissions from desalination plants). The results indicated that the current municipal water management system was generally inefficient and associated with high costs, which were expected to increase over time if the current supply-side management approach continued. Rising temperatures would further exacerbate these challenges. However, the study suggested a significant potential for reducing municipal water demand and its associated costs by the year 2030.

3.2 SWAT MODEL

The SWAT model is a semi-distributed, physically-based simulation model used for predicting how changes in land use and management practices affect the hydrological patterns in watersheds. It is designed to handle watersheds with diverse soil types, land-use patterns, and management conditions over extended time periods, primarily serving as a tool for strategic planning (Arnold et al., 1998; Neitsch et al., 2005). SWAT has the capacity to model individual watersheds or a network of interconnected watersheds in a given geographical area (Neitsch et al., 2011). The conceptual framework of the SWAT model is illustrated in Figure 3.

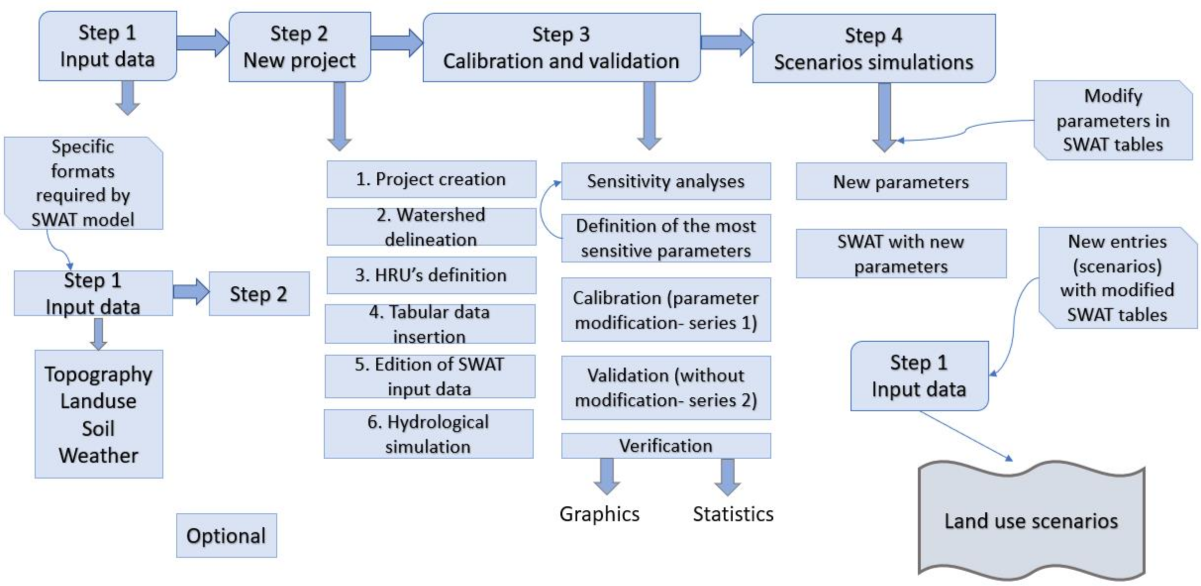

Figure. 3: Conceptual framework of the SWAT model (Andrade *et al.*, 2020)

3.2.1 Forecasting the impact of climate change on the management of water resources through the utilization of the SWAT model.

In recent times, Global Climate Models (GCMs) have become valuable tools for forecasting future climate changes. Several studies have incorporated outputs from various GCMs to model water resources management in conjunction with socio-economic considerations. For instance, Jin and Sridhar (2011) conducted simulations in the Boise and Spokane River Basins, focusing on basin-scale hydrology. They combined downscaled precipitation and temperature projections from a range of GCMs with the SWAT model to assess the impact of climate change on water resources in the region. Their study revealed a wide range of projections for precipitation and temperature between 2010 and 2060. In the Boise River Basin, precipitation changes varied from -3.8% to 36%, while temperature changes ranged from 0.02 to 3.9 °C. In the Spokane River region, precipitation changes were anticipated to fall between -6.7% and 17.9%, with temperature changes ranging from 0.1 to 3.5 °C over the next five decades. Peak flow changes (March through June) in the Boise River Basin were projected to span from -58 to +106 m3/s, and in the Spokane River Basin, the range was expected to be between -198 m3/s and +88 m3/s. Consequently, both basins exhibited significant variability in precipitation, evapotranspiration, and recharge estimates, providing stakeholders with diverse options for their decision-making processes.

Another study by Abbas et al. (2016a) applied the SWAT model to the Khabour Basin in Kurdistan, Iraq, using monthly time steps. This study utilized weather data, including daily and 0.5-hourly precipitation, maximum and minimum temperatures, and streamflow data. The model was calibrated and validated at the Solo Zakho discharge station to simulate streamflow. The calibrated model was then employed to identify trends in water components over the last three decades and assess the impacts of climate change in the near future (2046-2064) and distant future (2080-2100) under three emission scenarios (A2, A1B, B1) using six GCMs. All model runs under the three emission scenarios predicted that the catchment would experience decreased precipitation, blue water, and green water flows in both the near and distant futures, compared to the period from 1980 to 2010. The study's outcomes hold promise for identifying effective strategies for water resources management and agricultural practices in the future. Adhikari and Nejadhashemi (2016) conducted a similar study, examining climate change's effects on water resources in Malawi. They utilized downscaled data from six GCMs for the extreme Representative Concentration Pathway (RCP 8.5) as input for the SWAT model. Their findings indicated a range of changes at the country level, such as a -5.4% to +24.6% alteration in annual rainfall, a -5.0% to +3.1% change in annual evapotranspiration, and an increase from –7.5% to over +50% change in annual surface runoff and water yield, with up to an 11.5% increase in annual soil moisture. Regional analysis revealed increasing rainfall and evapotranspiration in the north and a gradual decline towards the south. Sub-basin analysis suggested a high likelihood of increased annual precipitation, surface runoff, water yield, and soil moisture, especially in the northern regions. The north appeared more susceptible to floods, while the southern regions were at greater risk of droughts.

Similarly, Abbas et al. (2016b) employed the SWAT model to assess climate change impacts on water resources in the Al-Adhaim Basin in Northeast Iraq. They used six GCMs under three emission scenarios and projected temperatures and precipitation into the SWAT model. The research aimed to compare water resources in the basin with baseline data from 1980-2010. Calibration and validation results demonstrated the model's effectiveness in simulating hydrological processes, with good agreement between the models and observed data. The results indicated that the entire basin might experience extreme aridity in the near and distant future, providing insights for future water resources management and crop production.

Huyen et al. (2017) predicted and evaluated water resource changes in the Srepok watershed in the central highlands of Vietnam, considering various climate change scenarios using the SWAT model. The study employed observed weather data (temperature and precipitation) and climate change data derived from dynamic downscaling of global change scenarios generated by the ECHAM4 GMC and the use of the PRECIS regional climate model (RCM). Calibration and validation were conducted for a baseline period (1990–2010), while for investigating the impacts of climate change scenarios on streamflow, two emission scenarios, A1B and A2, were separated into two future periods (2011–2039 and 2040–2069). The validated model parameters were then applied to these scenarios. Comparing the model output of climate scenarios to the baseline period, the study made the following conclusions: In all climate change scenarios, future minimum and maximum daily average temperatures would rise, and the annual precipitation would decrease in scenario A1B while increasing in scenario A2. Consequently, annual water discharge in scenario A1B decreased by 11.1% and 1.2% during the second and third periods compared to the first. In scenario A2, annual water discharge increased by 2.4% during the second period but decreased by 1.8% during the third period.

Aryal et al. (2018) aimed to quantify uncertainty sources in assessing climate change's impact on hydrology in the Tamakoshi River Basin in northeastern Nepal. They employed four Regional Climate Models (RCMs) - ACCESS 1, CNRM, MPI, and REMO - to project future climate in the study area. These models shared the same spatial resolution (0.44° × 0.44°), emission scenarios (RCP 4.5 and RCP 8.5), and future climate period (2006–2099). The study utilized multiple climate and hydrological models to simulate future climate conditions and discharge in the basin. The results showed projected temperature and precipitation changes in the near-, mid- and far-future periods. Maximum temperature was expected to increase by 1.75°C under RCP 4.5 and 3.52°C under RCP 8.5. Minimum temperature was projected to rise by 2.10°C under RCP 4.5 and 3.73°C under RCP 8.5 by the end of the twenty-first century. Precipitation in the study area was anticipated to decrease by -2.15% under RCP 4.5 and -2.44% under RCP 8.5 scenarios. Both minimum and maximum temperatures were predicted to increase across the three-time periods, while precipitation was expected to decrease. The study concluded that uncertainties in future climate variables and river hydrology arise from the choice of climate models, RCP scenarios, bias correction methods, and hydrological models. In a study similar to those mentioned, Bajracharya et al. (2018) assessed the impact of climate change on the hydrological patterns of the Kaligandaki Basin in Nepal, employing the SWAT model. They utilized the ensemble downscaled CMIP5 GCM outputs (precipitation and temperature) for the RCP 4.5 and RCP 8.5 scenarios. Their findings indicated that, under the extreme RCP 8.5 scenario, the average annual temperature in the basin could increase by more than 4°C. Similarly, average annual precipitation in the basin might see an increase of up to 26% by the end of the century. The combined effects of increased temperature and precipitation exacerbated the impact on discharge and water yield, with an increase of over 50% at the basin's outlet. Snowmelt played a significant role in the increased discharge, with snowmelt expected to rise by up to 90% during the 2090s. In conclusion, the Kaligandaki basin does not appear to face water availability problems in this century, given the projected increases in precipitation, snowmelt, water yield, and discharge.

Stefanidis et al. (2018) conducted a study that analyzed the response of a Mediterranean river under various climate and socio-economic scenarios in Europe. They examined surface air temperature and precipitation projections from two climate models, GFDL-ESM2M and IPSL-CM5ALR, following bias correction with linear scaling from 1975-2010. The scenarios were based on combinations of RCPs and Shared Socioeconomic Pathways, focusing on the early century (2030) and mid-century (2060) to represent future climate conditions with specific socio-economic characteristics. Their study revealed that the scenario characterized by fast economic growth and intensive energy resource exploitation had the most significant impact on both abiotic indicators (nutrient loads and concentrations in water) and biotic indicators. Other future scenarios, such as consensus and fragmented, showed more diverse changes, largely influenced by projected climate conditions. The study highlighted that future scenario, particularly those in the mid-century, significantly affected both abiotic conditions and biotic responses. This underscores the importance of implementing catchment management practices to mitigate long-term ecological threats to water systems.

In a separate study, Tiwari et al. (2018) examined mid-21st century climate projections for the Satluj region in the western Himalayas using CMIP5 global climate models under RCP scenarios (RCP4.5 and RCP8.5). They selected seven GCM models to analyze historical and projected climate data for temperature and precipitation. The higher emission scenario, RCP8.5, was the primary focus, with RCP4.5 as the secondary scenario. All the global climate models indicated that the study area would experience increased temperatures by the mid-century, with statistically significant temperature trends at a 95% confidence level. The multi-model ensemble showed substantial variations among the models in their climate projections, with temperature fluctuations ranging from approximately 1.5°C to 5°C across various areas of the western Himalayas in all seasons. Precipitation projections had a spread of 0.3 to 1 mm/day in all seasons, with a greater reduction in precipitation expected from June to September under RCP8.5 compared to present climate conditions. In contrast, it was anticipated that precipitation levels would increase in the basin during the mid-21st century. In conclusion, the SWAT model, when combined with downscaled output, suggests that future conditions, particularly under RCP8.5, may lead to increased discharge during the winter and spring seasons.

IV. CONCLUSION

In the fields of hydrology, water resources, and related disciplines, researchers are increasingly turning to hydrological models to investigate and understand the potential consequences of future shifts in climate and land use. While modeling is inherently uncertain and probabilistic, it serves as a valuable tool for exploring the complex hydrological processes within a catchment area and how alterations in that catchment may influence these processes. This, in turn, allows us to project potential impacts that water resource managers might encounter in the coming decades. These studies demonstrate the importance of considering a range of emission scenarios and socio-economic factors when evaluating the potential impact of climate change on water resources. They also highlight the necessity of catchment management practices to mitigate ecological threats and ensure sustainable water management in the face of climate change.

This review focuses on modeling techniques for evaluating the impact of climate change on hydrology and water resources, emphasizing the importance of scenario-based studies utilizing WEAP and SWAT models. Numerous studies have aimed to simulate the consequences of scenario-driven climate changes on the hydrological system. These scenarios are created by incorporating data from SRES and RCPs provided by the IPCC, as well as national policies. The results of these climate change scenarios are then compared to identify the most appropriate and plausible scenarios for effective future water management strategies. It's essential to note that these scenario-based studies do not attempt to predict the actual future changes but instead strive to assess the potential effects of these changes.

While the majority of the reviewed studies have focused on examining the potential impacts of climate change on hydrology and water resources, it is argued here that these studies predominantly rely on GCM projections. Consequently, there is a clear need to develop climate change models that integrate Earth observation data and in-situ measurements to enhance understanding and bolster the reliability of climate change predictions. Additionally, the findings emphasize the need for multi-model ensemble approaches, as different climate models can produce diverse projections. This approach helps decision-makers better understand the range of potential outcomes and make informed choices for water resource management and adaptation strategies.

Overall, these studies provide valuable insights into the potential challenges and opportunities posed by climate change on water resources and underscore the importance of proactive planning and management in addressing future water-related issues.

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