A COMPARATIVE ANALYSIS OF SWAT AND HEC-HMS MODELS FOR RESERVOIR VOLUME DETERMINATION IN THE CONTEXT OF CLIMATE CHANGE

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Abstract: Accurate reservoir storage capacity assessment is essential for sustainable water resource management, particularly under the increasing uncertainties imposed by climate change. This article presents a comparative analysis of two widely used hydrological models—the Soil and Water Assessment Tool (SWAT) and the Hydrologic Engineering Center–Hydrologic Modeling System (HEC-HMS)—for reservoir volume determination under varying climatic scenarios. Through a review of recent studies and case applications in humid tropical watersheds in China, we evaluate the models' structural frameworks, input requirements, calibration processes, and performance in simulating streamflow, a critical input for reservoir volume estimation. Findings indicate that SWAT excels in capturing high-flow events and simulating land-use impacts, while HEC-HMS demonstrates strength in medium-flow conditions and flood forecasting. Both models show robust performance when integrated with GIS and remote sensing data, enhancing spatial accuracy in reservoir volume prediction. The selection between SWAT and HEC-HMS should consider watershed characteristics, data availability, and specific hydrological processes of interest. This study provides actionable insights for water managers and researchers in selecting appropriate hydrological modeling tools for climate-resilient reservoir planning and operation.

Keywords: SWAT (Soil and Water Assessment Tool), HEC-HMS (Hydrologic Engineering Center – Hydrologic Modeling System), Geographic Information Systems (GIS), Reservoir volume determination, Climate change, Hydrological modeling, Runoff simulation, Streamflow, Watershed management

Аннотация: Точная оценка емкости водохранилищ имеет важнейшее значение для устойчивого управления водными ресурсами, особенно в условиях растущих неопределенностей, обусловленных изменением климата. В данной статье представлен сравнительный анализ двух широко используемых гидрологических моделей — Soil and Water Assessment Tool (SWAT) и Hydrologic Engineering Center–Hydrologic Modeling System (HEC-

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HMS) — для определения объема водохранилищ в условиях различных климатических сценариев. На основе обзора последних исследований и примеров применения в условиях влажных тропических водосборов Китай проведена оценка структурных особенностей моделей, требований к входным данным, процессов калибровки, а также их эффективности в моделировании речного стока — критически важного входного параметра для оценки объема водохранилищ. Результаты показывают, что модель SWAT превосходно справляется с моделированием пиковых расходов и оценкой влияния изменения землепользования, в то время как HEC-HMS демонстрирует высокую эффективность при моделировании средних расходов и прогнозировании паводков. Обе модели показывают надежные результаты при интеграции с данными ГИС и дистанционного зондирования, что повышает пространственную точность прогнозирования объема водохранилищ. Выбор между SWAT и HEC-HMS должен учитывать характеристики водосбора, доступность данных и специфику изучаемых гидрологических процессов. Данное исследование предоставляет практические рекомендации для водохозяйственных организаций и исследователей по выбору подходящих инструментов гидрологического моделирования для планирования и эксплуатации водохранилищ с учетом изменения климата.

Ключевые слова: SWAT (Soil and Water Assessment Tool), HEC-HMS (Hydrologic Engineering Center – Hydrologic Modeling System), геоинформационные системы (ГИС), определение объема водохранилищ, изменение климата, гидрологическое моделирование, моделирование стока, речной сток, управление водосборными бассейнами.

Annotatsiya: Suv resurslarini barqarar boshqarish uchun suv omborlarining hajmini aniq baholash juda muhimdir, ayniqsa iqlim o'zgarishi tufayli yuzaga kelayotgan ortib borayotgan noaniqliklar sharoitida. Ushbu maqola turli iqlim o‘zgarishi sharoitida suv ombori hajmini aniqlash uchun keng qo'llaniladigan ikkita gidrologik model - Soil and Water Assessment Tool (SWAT) va Hydrologic Engineering Center–Hydrologic Modeling System (HEC-HMS) ning qiyosiy tahlilini taqdim etadi. Xitoy nam tropik suv havzalaridagi so'nggi tadqiqotlar va amaliy ilovalar sharhlari orqali biz modellarning tuzilma doiralari, kirish ma'lumotlariga talablari, kalibratsiya jarayonlari va suv ombori hajmini baholash uchun muhim kirish parametri bo'lgan oqimni modellashtirishdagi samaradorligini baholaymiz. Natijalar shuni ko'rsatadiki, SWAT modeli yuqori oqim hodisalarini va yer-sudan foydalanish ta'sirini modellashtirishda ustunlik qilsa, HEC-HMS modeli o'rta oqim sharoitlari va toshqinlarni prognozlashda kuchli tomonlarga ega. Ikkala model ham GIS va masofadan zondlash ma'lumotlari bilan birlashtirilganda,

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suv ombori hajmini prognozlashning fazoviy aniqligini oshirib, mustahsam natijalar ko'rsatadi. SWAT va HEC-HMS o'rtasida tanlov suv havzasining xususiyatlari, ma'lumotlarning mavjudligi va tadqiq qilinayotgan o'ziga xos gidrologik jarayonlarni hisobga olish kerak. Ushbu tadqiqot suv xo'jaligi mutaxassislari va tadqiqotchilar uchun iqlim o'zgarishiga chidamli suv omborlarini rejalashtirish va boshqarishda mos gidrologik modellashtirish vositalarini tanlash bo'yicha amaliy tavsiyalar beradi.

Kalit so'zlar: SWAT (Soil and Water Assessment Tool), HEC-HMS (Hydrologic Engineering Center – Hydrologic Modeling System), Geografik Axborot Tizimlari (GIS), Suv ombori hajmini aniqlash, Iqlim o'zgarishi, Gidrologik modellashtirish, Oqimni modellashtirish, Daryo oqimi, Suv havzasini boshqarish.

Introduction. Accurate quantification of reservoir storage capacity is crucial for effective water resource management, particularly given the escalating uncertainties introduced by climate change, which manifest as shifts in hydrological regimes and increased frequency of extreme weather events. Within this challenging context, hydrological models like the Soil and Water Assessment Tool and the Hydrologic Engineering Center-Hydrologic Modeling System offer robust frameworks for simulating complex hydrological processes and, consequently, assessing reservoir dynamics (Chathuranika et al., 2022). This article aims to provide a comprehensive comparison of SWAT and HEC-HMS, highlighting their strengths, limitations, and suitability for determining reservoir volumes under varying climatic scenarios. The article will specifically delve into their applicability for research focusing on the use of GAT technologies to determine reservoir volumes within the intricate framework of climatic change. Both models have demonstrated efficacy in simulating streamflow, a critical input for reservoir volume estimation, across diverse geographical and climatic settings (Shekar & Vinay, 2021) (Aliye et al., 2020). The choice between these models often depends on the specific characteristics of the watershed, data availability, and the particular hydrological processes of interest (Sharma et al., 2025). The selection of the most appropriate hydrological model for a given watershed is critical for achieving accurate simulated results, with the success of hydrological prediction heavily relying on the proper choice of model input parameters (Aliye et al., 2020). This underscores the importance of a detailed evaluation of each model's theoretical underpinnings and practical performance in relevant hydrological studies before application (Alemu et al., 2023). For instance, previous research has successfully applied both SWAT and HEC-HMS to simulate streamflow in various Ethiopian basins, demonstrating their utility in regions with comparable hydrological complexities (Aliye et al., 2020) (Chekole et al., 2024). This article will critically evaluate the structural components and operational methodologies of both SWAT

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and HEC-HMS, providing insights into their respective advantages and disadvantages for modeling water resource availability in a changing climate (Chathuranika et al., 2022). It will further examine how these models can be integrated with Geographic Information Systems and remote sensing data to enhance the precision of reservoir volume determination.

Methodology. The SWAT Model The Soil and Water Assessment Tool is a physically based, semi-distributed hydrological model developed by the U.S. Department of Agriculture's Agricultural Research Service in the early 1990s (Ahad & Shams, 2024). This model operates on a daily time step and is capable of simulating a wide range of hydrological processes, including surface runoff, groundwater flow, evapotranspiration, and channel routing across diverse spatial and temporal scales. Its modular structure allows for the incorporation of detailed land use, soil, and topographical data, which are crucial for accurate spatially explicit hydrological simulations. SWAT is particularly adept at simulating the impacts of land management practices and climate change on water quantity and quality in large, complex watersheds (Ansarifard et al., 2024). Furthermore, SWAT's integration with GIS interfaces facilitates the delineation of hydrologic response units, which are fundamental for its semi-distributed modeling approach, allowing for the simulation of heterogeneous watershed conditions (Shekar & Vinay, 2021). This approach enables a more nuanced understanding of runoff generation and contaminant transport compared to lumped models that treat the entire watershed as a single unit (Yeboah et al., 2023). Specifically, SWAT models can assess agricultural best management practices and their effects on water quality and quantity, providing a comprehensive framework for water resource planning and environmental management (Marshall et al., 2025).

Overview of the SWAT Model: The SWAT model's widespread utility stems from its ability to simulate various hydrological components, including snowmelt, groundwater interactions, and nutrient cycling, making it a comprehensive tool for water resource assessment (Bouslıhım, 2020). Its application extends to predicting the impact of land management on water, sediment, and agricultural chemical yields over prolonged periods in extensive watersheds characterized by varied soils, land use, and management conditions (Kloub et al., 2024). The model operates on the principle of mass, momentum, and energy conservation, employing conceptualizations like the curve number and pothole-based streamflow simulation for different regions (Dash et al., 2023). The model's robust framework integrates several key components such as weather, hydrology, soil temperature, plant growth, nutrients, pesticides, and land management, to provide a holistic view of watershed processes (Jha et al., 2007). This semi-distributed, process-based river basin model, developed by Arnold et al., is specifically designed to predict the

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effects of land management practices on water, sediment, and agricultural chemical yields across large, complex watersheds exhibiting varied soil types, land uses, and management conditions (Bouslıhım, 2020).

Key Features and Capabilities. One of the core strengths of SWAT lies in its continuous time-scale simulation capability, enabling it to model long-term hydrological processes and their responses to changing environmental conditions (Oduor et al., 2023). This feature is particularly valuable for analyzing the impacts of climate change on reservoir volumes and water availability over decadal scales. Furthermore, SWAT's ability to integrate diverse spatial datasets, including land use, soil types, and topographic information, enhances its accuracy in representing real-world watershed complexities, making it suitable for assessing the long-term sustainability of water resources (Meshesha et al., 2021). Moreover, its capacity to simulate the transport of sediments and nutrients further extends its utility beyond pure hydrological modeling, providing a more integrated assessment of water quality alongside quantity (Zhang et al., 2023). The model also uses a water balance equation to simulate the hydrological cycle within a sub-basin, accounting for precipitation, surface runoff, evapotranspiration, and groundwater interactions (Gasirabo et al., 2023) (Chathuranika et al., 2022).

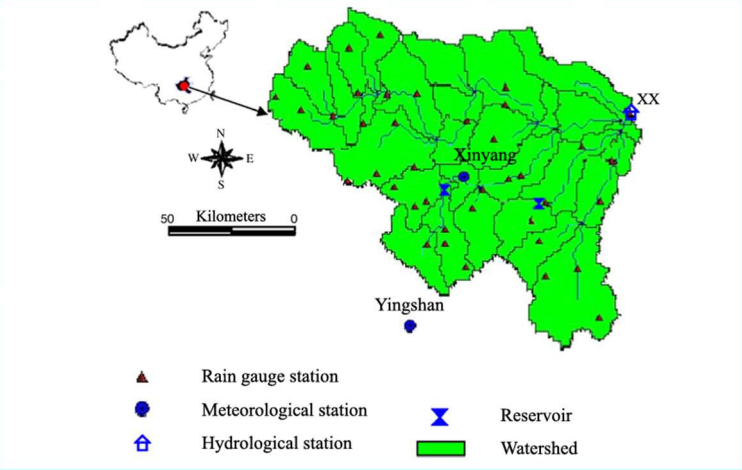


Figure 1. Processed results for SWAT for simulation

Applications in Water Resource Management**.** The SWAT model has been extensively applied in various studies, demonstrating its efficacy in hydrological modeling for water resource management, including assessing the impact of wetland drainage on streamflow and annual flow volumes (Perez-Valdivia et al., 2017). It has also been successfully employed to simulate streamflow in ungauged river basins and to evaluate the performance of different snowmelt algorithms in complex mountain regions (Perez-Valdivia et al., 2017).

The HEC-HMS Model. The Hydrologic Engineering Center's Hydrologic Modeling System is a sophisticated hydrological model specifically designed for simulating the precipitation-runoff processes in dendritic drainage basin systems (Şengül & İspirli, 2022). It excels in event-based simulations, focusing on the

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movement of water from precipitation to streamflow, and is particularly useful for flood forecasting and reservoir operations (Yu & Zhang, 2023) (Şengül & İspirli, 2022). HEC-HMS employs a variety of hydrological methods to simulate different components of the hydrological cycle, including rainfall-runoff transformation, baseflow, and channel routing, allowing for detailed analysis of watershed responses to precipitation events (Ranjan & Singh, 2022).

Overview of HEC-HMS Model:The model provides comprehensive tools for simulating various hydrological components such as precipitation, infiltration, surface runoff, and streamflow routing, making it adaptable for diverse watershed conditions and hydrometeorological events (Chathuranika et al., 2022). It is widely used for studies ranging from flood forecasting and flood damage reduction to reservoir design and operation, as well as urban drainage and water availability (Chathuranika et al., 2022) (Chiang et al., 2022). The HEC-HMS modeling system integrates three main components: the basin model, which defines the topographic and physical characteristics of the watershed; the meteorological model, which processes climatic data; and the control manager, orchestrating the simulation (Şengül & İspirli, 2022).

Key Features and Capabilities. The HEC-HMS model is adept at simulating intricate hydrological processes, offering a range of methods for computing losses (e.g., Soil Moisture Accounting), transforming excess precipitation into runoff (e.g., Clark Unit Hydrograph), and routing flows through channels and reservoirs (e.g., Muskingum-Cunge). Its distributed modeling capabilities have shown superior performance compared to lumped models, achieving a Nash–Sutcliffe efficiency of 0.88 for distributed simulations versus 0.51 for lumped approaches in specific applications (Tu et al., 2020).

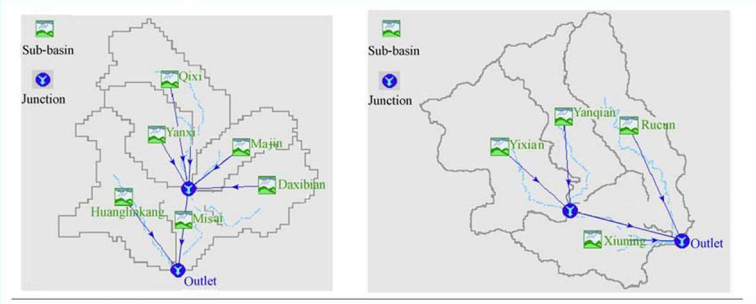


Figure 2. Processed results for imported to HMS for simulation

Applications in Hydrologic Analysis. The HEC-HMS model is extensively utilized for flood magnitude and frequency analysis, flood warning systems, and the planning of spillways and reservoirs (Ali et al., 2021). Its broad applicability encompasses urban drainage analysis, stream restoration efforts, and the assessment of water availability for diverse purposes, making it a versatile tool in water resource planning and management (Dhanapala et al., 2022). The model incorporates several key components such as the basin model, meteorologic model,

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control specification, time-series data, and terrain data to establish a robust simulation environment for rainfall-runoff mechanisms (Chiang et al., 2022).

Comparative Analysis of SWAT and HEC-HMS. While both the Soil and Water Assessment Tool and the Hydrologic Engineering Center's Hydrologic Modeling System are widely adopted hydrological models, their underlying architectures, data requirements, and optimal applications differ significantly (Alemu et al., 2023). Specifically, HEC-HMS typically excels in event-based simulations, focusing on the rapid transformation of precipitation to runoff for flood forecasting and reservoir operations, while SWAT is designed for continuous, long-term simulations to evaluate the cumulative impacts of land use and climate change on water resources (Ali et al., 2021). This distinction arises from HEC-HMS's lump-based or semi-distributed approach, which treats the basin as a homogeneous unit or discretizes it into fewer, larger elements, contrasting with SWAT's more detailed spatial discretization into homogeneous units of landform, soil, and topography (Chathuranika et al., 2022). For instance, HEC-HMS has been shown to be effective in flood simulation and hydrologic modeling, offering insights into physical watershed characteristics (Kazezyılmaz-Alhan et al., 2020). Conversely, SWAT is better suited for assessing the long-term hydrological impacts of various land management practices and climate change scenarios due to its continuous simulation capabilities and detailed spatial representation of watershed characteristics (Chathuranika et al., 2022). However, it is important to acknowledge that HEC-HMS has been successfully adapted for continuous simulations in certain contexts, particularly when integrating snowmelt processes for hydrological forecasting in mountainous regions (Şengül & İspirli, 2022). Nevertheless, while HEC-HMS can be adapted for continuous simulation, its primary strength lies in event-based modeling, particularly for short-term flood processes, making it less ideal for long-term water balance studies that require detailed interaction between surface and groundwater (Mo et al., 2020).

Strengths and Limitations. HEC-HMS, for example, proves highly effective for real-time flood forecasting and dam breach analysis due to its event-driven simulation capabilities and robust routing functions (Dhanapala et al., 2022). In contrast, the SWAT model's ability to simulate the long-term impacts of land management practices and climate change on water quantity and quality makes it suitable for assessing the effectiveness of various conservation strategies and predicting future water availability (Bouslıhım, 2020).

Suitability for Reservoir Volume Determination. For determining reservoir volumes in the context of climate change, the choice between SWAT and HEC-HMS depends critically on the research focus and data availability. While HEC-HMS can simulate reservoir operations and outflow, SWAT’s comprehensive

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representation of watershed processes, including water balance components and sediment transport over extended periods, offers a more robust framework for evaluating the long-term changes in water yield and reservoir inflow under varying climate scenarios (Chathuranika et al., 2022) (Kazezyılmaz-Alhan et al., 2020). Therefore, for a study focused on the cumulative effects of climate change on reservoir volumes, SWAT's continuous simulation and integrated processes generally provide a more comprehensive assessment (Chathuranika et al., 2022). However, the HEC-HMS model can be instrumental in extracting model-specific information, such as diversion, junction, reservoir, and sub-basin characteristics, which are crucial inputs for detailed hydrological simulations (Alemu et al., 2023).

Integration with Geospatial Technologies. Both HEC-HMS and SWAT models significantly benefit from integration with Geographic Information Systems for data pre-processing, parameterization, and visualization of results, allowing for efficient management of spatial data layers such as digital elevation models, land use, and soil types. This integration facilitates the preparation of model inputs, such as sub-basin delineation and stream network generation, and enhances the interpretation of simulation outputs through thematic maps and spatial analyses. This enables a more accurate representation of the physical characteristics of a watershed and improves the predictive capability of the models, especially when addressing complex hydrological phenomena. For instance, GIS can be utilized to generate Hydrologic Response Units for SWAT, ensuring that the model accurately reflects the spatial heterogeneity of a watershed (Perez-Valdivia et al., 2017). Similarly, HEC-HMS leverages GIS for automated retrieval of geographical parameters like area, flow length, and slope from Digital Elevation Models, facilitating the setup of basin models and sub-basin divisions (Chiang et al., 2022). The ArcGIS platform, with its advanced tools like Arc Hydro Tool and HEC-GeoHMS, plays a pivotal role in delineating watersheds and river networks, which are fundamental for both SWAT and HEC-HMS model parameterization (Ranjan & Singh, 2022) (Alemu et al., 2023).

Role of GIS in Model Parameterization. GIS-based tools, such as HEC-GeoHMS, are specifically designed to streamline the process of extracting basin characteristics and other essential input parameters directly from digital elevation models for hydrological models like HEC-HMS (Şengül & İspirli, 2022) (Belayneh et al., 2020). This capability allows for the automated analysis of spatial unevenness within a watershed, including river system distribution and the delineation of sub-basins, thereby enhancing the accuracy of hydrological simulations (Yu & Zhang, 2023). This includes the generation of slope and topographic elevation maps, as well as the identification of hydrologic soil groups,

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which are fundamental for determining infiltration rates and runoff potential within sub-basins (Ranjan & Singh, 2022).

Results: Furthermore, SWAT's ability to model sediment transport and nutrient cycling provides a more holistic understanding of reservoir sustainability, beyond just water quantity (Alemu et al., 2023). On the other hand, HEC-HMS excels in event-based simulations, making it suitable for analyzing specific flood events and evaluating real-time reservoir operations. However, for reservoir volume determination under climate change, SWAT's integrated approach to simulating basin-scale hydrological processes, including surface runoff, subsurface flow, and groundwater interactions, offers a more comprehensive framework for assessing long-term water availability and reservoir storage impacts. However, it has been observed that both models can accurately simulate low flows, with SWAT exhibiting slight under-predictions for dry and wet seasonal flows (2.12% and 13.52%) compared to HEC-HMS (10.76% and 18.54%) (Chathuranika et al., 2022). The choice between these models, therefore, hinges on the specific research question, with SWAT being generally preferred for long-term climate change impact assessments on water resources due to its comprehensive process representation, while HEC-HMS may be more suitable for detailed event-based flood forecasting or reservoir operations.

Conclusion. Given the overarching goal of determining reservoir volumes in the context of climatic change, the integration of advanced GAT technologies with models like SWAT and HEC-HMS offers a robust methodology for comprehensive hydrological assessment. Specifically, the SWAT model, with its capacity for continuous, long-term simulations of water balance components and explicit consideration of land use and climate change impacts, is generally more appropriate for the detailed analysis of reservoir volume dynamics under future climatic conditions (Chathuranika et al., 2022). This model also allows for the integration of various climate change scenarios to project future alterations in precipitation, temperature, and evapotranspiration, which directly influence reservoir inflow and storage capacity.

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