

Integrated Modeling Approaches to Enhance Water Sustainability in Philippine Watersheds: A Review of its Applications and Limitations

Milton Eero C. Perez^a, Jewel Brittany D. Pernia^a, Cybelle Concepcion M. Futralan^c, Mayzonee V. Ligaray^b, Angelo Earvin Sy Choi^{a,*}

^aDepartment of Chemical Engineering, De La Salle University, 2401 Taft Ave., Manila 0922, Philippines

^bInstitute of Environmental Science and Meteorology College of Science, University of the Philippines Diliman, Quezon City 1101 the Philippines

^cInstitute of Civil Engineering, University of the Philippines Diliman, Quezon City, 1101, Philippines

angelo.choi@dlsu.edu.ph

Water accessibility in the Philippines remains a critical challenge due to its increasing demand caused by increasing population and climate change. The complexity of water supply and demand within the watershed should be studied to focus on more sustainable management strategies addressing water-related issues. This review evaluates the application of numerous hydrological models such as the Water Evaluation and Planning System, Variable Infiltration Capacity, Water Erosion Prediction Project, and Soil and Water Assessment Tool in the prediction of water availability and its distribution systems under different conditions. These integrated frameworks support the evaluation of sustainable management scenarios for a more effective and efficient water utilization. With sound water management, long-term water security in the Philippines can be achieved. The use of hydrological models can offer stakeholders valuable information such as water hydrology, assess future scenarios in water systems, and guide strategic water allocation and conservation. This paper investigates the various advantages, limitations and their integration into decision-making for water quality monitoring, watershed management and adaptive infrastructure planning that are vital to achieve water security and water resilience in the Philippines. Optimized water management can decrease reliance in energy-intensive water supply systems and influence the use of renewable energy sources in the water industry.

1. Introduction

The Philippines has been actively implementing local solutions and strategies in an attempt to address wastewater management challenges and to achieve the Sustainable Development Goal 6 (SDG 6). Corpuz (2025) emphasized how the country has adopted Constructed Wetlands (CWs) and various decentralized treatment systems. CWs are known as nature-based solutions that significantly benefit rural areas as these are low-cost and effective. Watershed management strategies can help to increase water availability and promote more sustainable water use.

Understanding the balance of water supply and demand is critical in the Philippines, where water shortages, uneven distribution, and reliance on groundwater continue, particularly in rural and agricultural areas as about 60 % of the rural population relies on groundwater for drinking and irrigation (Carrard et al., 2019). Hydrological models are useful instruments for tackling these concerns because they simulate the complex dynamics of the hydrological cycle. The Soil and Water Assessment Tool (SWAT), Water Evaluation and Planning (WEAP), Variable Infiltration Capacity (VIC), and Water Erosion Prediction Project (WEPP) are models that estimate water availability, predict soil erosion, and guide water resource management decision-making (Prasad et al., 2020).

Beyond simulation, integrated hydrological and water quality models offer a more holistic approach to watershed management. These models facilitate evidence-based planning and reaction by analysing water availability, forecasting runoff and erosion, and estimating pollution transport. When used together, models like WEAP, VIC,

SWAT, and WEPP provide complimentary insights ranging from large-scale climate variability to localised watershed behaviour, allowing planners to build more resilient and adaptable water plans (Keller et al., 2023). This review critically examines the use of hydrological models in Philippine watersheds, discusses their strengths and limitations, and investigates how they can be integrated into water quality monitoring, watershed management, and adaptive planning strategies to support long-term water sustainability.

2. Water Supply and Demand in the Philippines

2.1 Water Supply

The Angat Dam remains the primary raw water source of the Metropolitan Waterworks and Sewerage System (MWSS). The MWSS is allocated 51 % of the granted water supply volume of the dam of $72.9 \times 10^6 \text{ m}^3$ for its covered areas, and the balance is transported to the Angat Maasim River Irrigation System (AMRIS). A study reported that while the granted volume for the metropolitan areas is 46 m^3 per second, the dam was only able to supply an annual average volume of 38.6 m^3 per second from 2001 to 2010 (Cheng, 2014). Moreover, hydrological conditions and forecasts such as heavy rainfall caused projections of a decrease in the runoff dam volume of up to $200 \times 10^6 \text{ m}^3$ in 2035, which can amplify issues in water supply.

Water privatization addresses inefficiency but raises socioeconomic and political issues. Lack of government funds and budget allocation led to the MWSS owing approximately a PHP 405×10^6 debt to the Asian Development Bank (ADB) and the World Bank (WB) while improving local water efficiency systems (Encarnacion Tadem, 2020). This urgency led to the 1997 privatization of public water service provider. Another motive for the approach is that private companies could provide for communities not covered by the MWSS. The two main water concessionaires, Maynilad and Manila Water informed the public of the following benefits after privatization: lower annual water rates, uninterrupted water service, and 100 % water coverage for ten years. Six years after privatizing MWSS, the public experienced an abrupt 81 % rate increase in the east zone and 36 % in the west zone in January 2003.

Consumer groups argue that water privatization aided corrupt activities on both national and municipal scales. A 2019 report stated that to ensure the promised uninterrupted water service, Manila Water dedicated a PHP 180×10^6 budget for the development of water resources and facilities. These promised developments never materialized. Social and income inequalities have also become an issue during the privatization of water services. Based on a 2022 survey, with Quezon City as its study area, 41 % of low-income families choose not to rely on piped water from Maynilad because of high costs, especially with installations and maintenance (Alfonso et al., 2022).

2.2 Water Demand

Pricing structures influence water demand, as increased prices reduce water consumption. Philippine households in the northern part of Metro Manila, on average, consume 7.75 m^3 of water monthly. This consumption results in an average water bill rate of PHP 90 per m^3 (Palanca-Tan, 2020). The regression analysis of the study also shows that there is a 0.0335 m^3 increase in demand with every PHP 1 increase in water prices. The correlation implies that efficient water systems are inaccessible and inadequate for families with below-average income and households of larger sizes. Castilla et al. (2024) emphasized that population size significantly impacts water demand. The results show that a 5.0 % projected increase in the number of households in Danao City will cause an 8.5 % increase in water demand and consumption. This demand is expected to be fulfilled by a 26 % projected growth in water supply from 2024 to 2028. Population growth in provinces threatens mountain water security, highlighting the need for sustainable management.

2.3 Water Security

One of the local areas that faces a critical water supply and demand imbalance is Metro Manila, along with Baguio and Cebu City. Malayang III (2014) reported that the MWSS and its micro-networks are projected to supply only 80 % of the expected water demand of 1.9×10^6 cubic meters in 2010. Despite the assumption of increased economic growth, it is also projected that Central Luzon will experience a negative water balance until 2025. The projections mentioned are mainly due to population growth, which allows increased water demand. The demand-supply imbalance resulted in a crisis in 2019 when Manila Water declared a state of low water pressure to no water in Metro Manila after the abrupt drop in the water level in the La Mesa Dam (Torio et al., 2021). The dam showed signs of critical water levels as early as 2018. The decline of water levels quickened as Manila Water took out water from the dam in an attempt to meet the rising water demand. During this time, the water level of the dam reached the warning level of 160 m, which is 50 m below the normal level (Rocina, 2023).

2.4 Water Quality

A study by Branzuela et al. (2022) reported that watersheds with sufficient water supply limit people from accessing potable water due to water contamination. A watershed management plan can be utilized to maximize the water available in the area which leads to a more sustainable water resource. Alternative water resources strategies such as the Integrated Water System (IWS) that is comprised of three systems which are the Rainwater Harvesting System (RWHS), Water Treatment System (WTS), and Eco-Toilet System (ETS), can lessen the reliance on water supply within the watershed, enhancing the water availability in the area (Ignacio et al., 2019). The water quality degradation of rivers necessitates effective integrated water resource management strategies that balance ecological health with human needs. Implementing policies that promote sustainable land use practices within watershed areas can mitigate pollution sources and enhance overall river health. It is highlighted in recent studies that integrating diverse water quality data sources is significant for sustainable and efficient water resource management. Integrating the community perspective and incorporating it with scientific data and geospatial analysis tools are vital for sustainable water management to address water quality challenges (Mishra et al., 2024). All aspects of integrated water resource management were considered to effectively address water quality and quantity. By utilizing these integrated water management approaches, holistic ecological characterization, enhanced water resource strategies, and fair access to water quality data for policy making can be achieved.

3. Hydrologic Models

Table 1 presents an overview of the hydrological models: SWAT, WEAP, VIC, and WEPP. The purpose, components, focus, and output of the models are all compared based on their application.

Table 1: Overview of SWAT, WEAP, VIC, and WEPP Hydrological Models

	Soil and Water Assessment Tool	Water Evaluation and Planning System	Variable Infiltration Capacity	Water Erosion Prediction Project
Purpose/ Objective	To evaluate the impacts of land management practices on water resources within watersheds	To stimulate water resource systems	To facilitate water and energy balance in land surface areas on a macro scale	To predict and simulate water runoff, soil erosion, and sediment movement
Components/Parameters	Physical characteristics of watersheds	Water supply and demand sites, physical characteristics of watersheds	Soil and hydrologic parameters	Soil and hydrologic parameters
Focus	Simulating long-term hydrological responses to various environmental conditions and management strategies	Allows for the modelling of water supply and demand sites, and the interactions between them	Assesses water resources and project groundwater conditions by simulating water and energy balances	Provides insights into how sediment moves through landscapes under various conditions.
Output	Long-term hydrological responses	Breakdown of water inputs and outputs	Water and energy balance simulation	Erosion predictions

3.1 Soil and Water Assessment Tool

SWAT is a widely used hydrological model used to evaluate the impacts of land management practices on water resources within watersheds. According to Yates et al. (2005), this model is effective for simulating long-term hydrological responses to various environmental conditions and management strategies. Recent studies have demonstrated the effectiveness of SWAT in stream flow simulation across various land-use scenarios. Furthermore, the SWAT model has been utilized to assess the impacts of climate change on water availability. Tan et al. (2019) noted several advantages and disadvantages of using the SWAT model. One of its main advantages is that the model can adapt to various temporal scales. This allows the users to simulate scenarios on different time bases. Another strength is the friendly user interface of SWAT. The SWAT editor and the

SWAT-CUP tool reduce potential complexities during model setup and implementation. This makes the model easy to use for a wide range of users, even those with limited experience. Despite these advantages, SWAT has several limitations that impact its efficiency and accuracy. The mentioned study emphasized the significance of extensive input data for the model, implying that the lack of availability hinders the accuracy of the output. The study by Principe and Blanco (2013) utilized the SWAT model to simulate and analyze the effects of climate change and land use and land cover (LULC) changes on soil loss rates in the Cagayan River Basin. By integrating projected climatic parameters and land use/land cover (LULC) alterations into the model, the study estimated a potential increase in soil loss rate of up to 37 % relative to the baseline conditions. Moreover, it offered a comprehensive analysis of the sediment dynamics and proposed practical measures that can help mitigate soil erosion with the ongoing environmental changes.

3.2 Water Evaluation and Planning

The WEAP model is designed to stimulate water resource systems, integrating both hydrological and anthropogenic components. It allows for the modelling of water supply sources, demand sites and the interactions between them. According to Yates et al. (2005), the model operates on a network basis, where nodes represent different components like watersheds and demand sites, connected through transmission links. The concept of WEAP was developed by SEI (Stockholm Environment Institute) in 1988. The fundamental concept of maintaining water balance is the main function of WEAP, which can be applied in the agricultural and municipal systems and a single or complex watershed and river basin systems. Its features are composed of an intuitive GIS-based graphical interface that allows users to view, construct, and modify configurations. Additionally, it WEAP is utilized for projecting demand and supply to allocate water resources effectively and to implement water resource management strategies and policies.

The WEAP model poses various strengths and limitations in water simulations and modeling experience (Kandera and Výteta, 2020). The study emphasized that WEAP can integrate water components such as surface water, groundwater, and water quality. This integrated approach helps users assess interactions between different water sources and their supply and demand. This implies that the lack of detailed data input could lead to output inaccuracies. Gao et al. (2017) observed that the model tends to simplify simulations of hydrological processes. The Integrated Water Resources Management (IWRM) framework involves various models for water resource management, among which the WEAP model is one of the widely utilized models successfully applied globally. The WEAP methodology is a versatile tool considering its user-friendly interface for regulating scenario analysis and data input. It is capable of assessing water scarcity, exploring possible management strategies that are cost-efficient, and projecting climate change impacts (Yang et al., 2018).

3.3 Variable Infiltration Capacity

The VIC model aims to facilitate water and energy balance in land surface areas on a macro scale. VIC models are commonly integrated with local climate change data to assess water resources and project groundwater conditions. Process-based models like VIC require components such as transpiration, precipitation, and runoff generation. The model simulates the water and energy balances using soil and hydrologic parameters (Xia et al., 2018). These balance simulations are categorized using two modes: water mode and energy mode.

Notable advantages and disadvantages are present in the VIC model (Safeeq et al., 2014). One of its benefits is the capacity of the model to capture interannual variability of streamflow. This is essential for watershed assessment, especially for understanding water trends and changes over time. The VIC model enhances projection reliability by integrating meteorological data and accounting for climate change conditions.

Scheidegger et al. (2022) reported projections for future hydrological conditions in Panay and Pampanga up to 2089 using the VIC model. The results show that the precipitation rate around Pampanga is expected to decrease by 2 % to 4 % in 2080, which shows that there is a need for proper water supply management. According to the researchers, the VIC model effectively simulated hydrological discrepancies in certain flow conditions were observed; further research could improve the accuracy of the model. The VIC model can capture sub-grid variability which makes it the most efficient model for large-scale modeling among the other well-known models (Nandi and Reddy, 2022). VIC can be improved by integrating a flexible runoff generation mechanism that accounts for subsurface stormflow in unsaturated zones, enhancing its performance and simulation accuracy (Yi et al., 2023). However, a study by Damavandi et al. (2019) proposed utilizing machine learning techniques for more efficient runoff prediction. These findings can help modify the VIC model and enhance its performance through data integration and comparative model analysis.

3.4 Water Erosion Prediction Project

The WEPP model is a continuous, process-based erosion prediction model that is capable of estimating soil loss and the runoff along a slope. It predicts and can simulate water runoff, soil erosion, and sediment movement across landscapes. Bavor and Genson-Torrefranca (2016) applied the model to simulate scenarios and to

predict soil erosion over a watershed. The study was able to produce several scenarios that showed a significant reduction in soil erosion. The study by Puno et al. (2015) predicted sediment yield and water discharge of 22.3 and 23.3 x 10⁶ cubic meters per year, respectively. Both studies prove how WEPP is effective in soil and sediment application.

The WEPP model provides insights into how sediment moves through landscapes under various conditions. In a study by Rondius (2012), which focused on the Pasig River, researchers utilized WEPP to analyze sediment delivery from upstream agricultural areas. The findings revealed that approximately 40 % of the sediment entering the river system originated from eroded agricultural fields, emphasizing the need for targeted interventions in these areas. In the study of Han et al. (2016), the WEPP model was applied to accurately model erosion at the slope scale in the Loess Plateau, but it tended to overestimate runoff and erosion at the watershed scale. In northeastern Oregon, WEPP has effectively simulated the hydrology, sediment transport, and crop growth in both no-tillage and conventional systems that required minimal calibration (Williams et al., 2010). These studies highlighted the capabilities of integrating WEPP models in modelling erosion and hydrology under various conditions, whilst identifying the need for refinement of the ecosystem.

4. Conclusion

The assessment of water supply and demand within Philippine watersheds is critical for creating effective and adaptable water resource plans. This analysis assessed four main hydrological models—SWAT, WEAP, VIC, and WEPP—each with unique strengths for simulating watershed processes. SWAT and WEPP are particularly useful for assessing erosion, runoff, and sediment transport under a variety of land-use scenarios. VIC delivers reliable macro-scale forecasts of water and energy balances, which are required for long-term climate impact assessments. WEAP, on the other hand, combines hydrological and socioeconomic components to aid planning and policy formulation in areas with complicated water demand patterns.

Despite their potential, various barriers prevent widespread adoption in the Philippines. These include a scarcity of high-resolution and long-term data, insufficient technical competence for model calibration and interpretation, and fragmented coordination among local authorities. To address these limitations, academic-industry collaboration is required to build data infrastructure, promote open-access platforms, and increase technological capability. Recognizing the strengths and limitations of present frameworks, this research emphasises the significance of integrated and inclusive modelling in developing adaptive water management. The strategic application of hydrological models can help drive resilient planning and enhance long-term water sustainability in the Philippines.

Acknowledgments

This work is supported by the Natural Sciences Research Institute of the College of Science, University of the Philippines Diliman under the Project Code ESM-21-1-01 and the Department of Science and Technology Science National Research Council in the Philippines under the code N8-433-32.

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