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Review of soil and water assessment tool studies on erosion and sedimentation in Sulawesi

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ABSTRACT

Although the soil and water assessment tool (SWAT) is frequently used in hydrological research to assess sedimentation and erosion, its use throughout Sulawesi has not yet been synthesized. With an emphasis on identifying research trends, methodological practices, and knowledge gaps, this study attempted to review and compile previous SWAT-based studies conducted in Sulawesi watersheds. A review was utilized journal articles, conference proceedings, and university repositories published between 2010 and 2024. Research sites, goals, input data, calibration and validation procedures, as well as published results were all included in the scope. This synthesis places more emphasis on methodological gaps and patterns than on comprehensive coverage. Twenty-two studies in all were found. While central, west, and southeast Sulawesi continue to be underrepresented, south Sulawesi accounted for more than half. Land cover change, conservation tactics, the availability of water resources, micro-hydro potential, and flood risk assessment were the primary research topics. However, scenario development was frequently lacking, and only 55% of studies reported calibration and validation using numerical metrics (e.g., NSE, R2, PBIAS). Few studies included socioeconomic factors, which diminished the applicability of the model's outputs for policy. This is the first review that the authors are aware of, focusing exclusively on Sulawesi.

Keywords: SWAT, sedimentation, erosion, watershed, Sulawesi, conservation, land use.

INTRODUCTION

Damage to watersheds (DAS) is a serious challenge in natural resource management in Indonesia, mainly due to land degradation, sedimentation, and declining water resilience. Soil erosion is the primary cause, exacerbated by uncontrolled land conversion and inappropriate land-use practices. In response to this, Baja (2002) emphasized the importance of a GIS-based spatial approach in accurately assessing land potential. Changes in land use and land cover, he argued, must be carefully considered in hydrological analysis, as they have a direct impact on erosion, surface runoff, and water balance in the watershed area.

To address the challenges in watershed management, the soil and water assessment tool (SWAT) model was developed by the USDA in the early 1990s as an open-source semi-distributed hydrological modeling tool (Arnold et al., 1998; 2012). SWAT divides watershed areas into hydrological response units (HRUs) based on land cover, slope, and soil type, and was originally designed for large-scale watersheds (Arnold et al., 1998). This model is flexible for analyzing the impact of land use change, conservation practices, and climate on hydrology and water quality (Gassman et al., 2007; 2014). Calibration support and uncertainty analysis through SWAT-CUP further strengthen its function in water resource studies (Abbaspour et al., 2000).

The SWAT model has been widely used to analyze the impact of land use change and climate variability on the hydrological response of a watershed. Changes in land cover and rainfall patterns have been shown to influence surface flow dynamics, sedimentation, and water availability. For example, climate change has a significant impact on water resource components (WRC) that are crucial in supporting agricultural productivity (Toma and Meja, 2025). Additionally, climate change also affects reduced crop yields, such as corn, through decreased evapotranspiration efficiency (ET) and crop water productivity (CWP), as found in a study in the Liao River Basin (Zhang et al., 2023). Increased rainfall intensity has also heightened the risk of flooding and surface runoff (Waheed et al., 2024).

Not only climate change, but changes in land use and land cover (LUCC) have also been shown to alter the water balance and hydrological response. In the loess hill watersheds of China, the conversion of agricultural land to residential areas resulted in an increase in surface runoff of 14.26–36.15% and an increase in water yield of 5.13–15.55% (Liu et al., 2023). Conversely, converting agricultural land into grassland reduced surface runoff by up to 12% and reduced nitrate nitrogen loads by up to 68% (Strugała and Bochenek, 2023). Increased vegetation cover has also been shown to support water infiltration and increase soil moisture content, as observed in the Ethiopian Highlands (Waheed et al., 2024).

The SWAT model can be one alternative approach to determining the best water resource management practices in Indonesian watersheds. This model has demonstrated fairly accurate performance in tropical climates. In Indonesia, the SWAT model has been widely used to analyze erosion and sedimentation across various islands. In Sulawesi (Mamasa sub-watershed), SWAT mapped high sedimentation in downstream areas due to forest conversion into agricultural land, with sediment loads exceeding 1,400 tonnes/ha/year (Isra et al., 2023). In East Java (Genting Watershed), the AVSWAT2000 model identified an average erosion rate of 49.19 tonnes/ha/year and suggested vegetative conservation as a solution to reduce sedimentation (Lufira et al., 2022). In south Kalimantan (Sungai Besar watershed), average sedimentation reached 58.48 tonnes/ha/year, with erosion distribution classified from very light to moderate (Febrianti et al., 2018).

In west Papua (Kais watershed), the use of SWAT+ shows that oil palm plantations increase runoff by 21% and sedimentation by 16.9%, and significantly worsen water quality (Asmara and Randhir, 2024). In central Lombok, SWAT shows that community forests contribute to reducing runoff and erosion as the age of the forest increases (Nandini, 2019). Meanwhile, in south Sumatra (Komering watershed), SWAT is used to map erosion risk and support the determination of priority conservation sub-watersheds (Salsabilla and Kusratmoko, 2017).

Overall, the SWAT model has great potential for application in the areas with complex topography, high ecosystem diversity, and limited data, such as Indonesia. However, despite its widespread use in Java, Sumatra, Kalimantan, and parts of south Sulawesi, the application of SWAT for erosion and sedimentation studies in other provinces on Sulawesi Island, such as southeast Sulawesi, central Sulawesi, and west Sulawesi, remains relatively limited and has not been fully structured. Yet, these regions have watershed characteristics that are highly vulnerable to erosion and sedimentation due to heavy rainfall, steep topography, and massive land-use changes over the past two decades.

Therefore, this article aimed to review and provide an overview of the use of the SWAT model in erosion and sedimentation studies in Sulawesi. The focus of the study was directed at identifying research trends that have been conducted, evaluating the effectiveness of the model in the local context of each watershed (DAS), and exploring the potential for developing the SWAT model to support adaptive and sustainable watershed management.

The specific objectives of this review were to: (i) identify important knowledge gaps and suggest a research agenda for enhancing SWAT applications in erosion and sedimentation studies; (ii) assess methodological rigor, particularly calibration and validation practices; and (iii) document the spatial distribution and thematic scope of SWAT applications across Sulawesi between 2010 and 2024. The goal was to provide a thorough summary of research trends, highlight methodological flaws, particularly about calibration and validation procedures, and identify the opportunities to enhance SWAT applications in Sulawesi erosion and sedimentation studies. Figure 1 provides a summary of the temporal trends in publications.

REGIONAL DISTRIBUTION OF SWAT STUDIES IN SULAWESI

The SWAT has been utilized in various ways to investigate erosion and sedimentation in Sulawesi. This section tells a story about some critical studies, organized by province to reveal patterns in space, the main areas of research, and gaps in the current body of knowledge. it is easier to conduct spatial analysis and compare results from different studies and SWAT applications in each region because the data is broken down by province.

South Sulawesi

Most SWAT studies in Sulawesi are concentrated in south Sulawesi, particularly in the Mamasa, Jeneberang, and Bila watersheds. These studies generally examine the impacts of land use change, water availability, and conservation practices. For example: One of the river basins (DAS) that has been the focus of most studies in South Sulawesi is the Mamasa River Basin. Recent studies indicate that the conversion of forests into agricultural and plantation land in the downstream area has triggered an increase in sedimentation and annual discharge, reflecting serious pressure on the hydrological balance (Irlan et al., 2022; Isra et al., 2023). In response to this situation, the importance of aligning land use with spatial planning has been reaffirmed as a key strategy in controlling erosion and sedimentation (Anila et al., 2020). Land conservation efforts such as the implementation of bunch terraces, strip grass, and agroforestry have also proven effective in reducing surface runoff and sediment load (Murtilaksonoa et al., 2017).

Land cover changes leading to the dominance of cultivated land or settlements continue to be associated with increased surface runoff. In the Bila watershed, this phenomenon is illustrated by the shift in function from shrubland to open land and agriculture, which has resulted in increased surface runoff (Wahyuni and Salimin, 2023). A similar situation occurs in the Jeneberang watershed, where the loss of forest cover has contributed to increased runoff and decreased base flow (Putera et al., 2020). In the Koro Bakara watershed, the conversion of protected forests into pepper plantations has increased the risk of flooding and highlighted the mismatch between actual conditions and existing spatial plans (Fitrian and Boro, 2021).

In addressing these issues, the land use scenario approach has been widely used to design adaptive mitigation strategies. A study in the Karajae watershed shows that optimizing forest areas in land use scenarios can reduce discharge and sedimentation compared to actual conditions (Chairil et al., 2021). Water availability projections in the Maros watershed also show fluctuations that require further spatial analysis for sustainable water resource management (Mandy et al., 2020). A decrease in base flow due to vegetation degradation is reflected in the Tanralili sub-watershed (Surahman et al., 2021), while in the Lisu watershed, land use simulations show that the implementation of spatial plans can increase infiltration and reduce runoff and sedimentation (Samsul et al., 2019). In the context of renewable energy, spatial planning implementation in the Kelara watershed actually reduces the potential for small hydropower development due to the decrease in available minimum flow (Muis et al., 2020). Meanwhile, in the Jenelata watershed, projections up to 2032 indicate a decrease in water availability

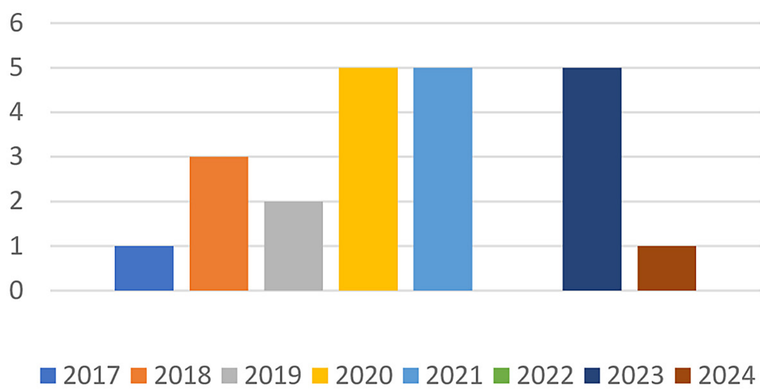

Figure 1. Distribution of SWAT model publications in Sulawesi based on year of publication (2017–2024)

and an increase in carbon emissions, underscoring the importance of land use guidelines that consider hydrological balance and emission reduction (Nursaputra et al., 2021).

In addition, SWAT-based modeling is also used to estimate flood risk and support disaster mitigation efforts. In the Bila watershed, changes in land cover have caused peak discharge to exceed river capacity, increasing the region's vulnerability to flooding (Sholichin and Qadri, 2020). Meanwhile, climate change projections in Bantimurung-Bulusaraung National Park indicate the potential for a significant expansion of flood-affected areas, underscoring the importance of integrating climate analysis into watershed planning (Barkey et al., 2019). These findings collectively reinforce the role of SWAT models as an important tool in supporting sustainable and adaptive watershed management in response to land and climate change.

North Sulawesi and Gorontalo

In contrast, the studies in north Sulawesi and Gorontalo are fewer in number but provide valuable insights into hydrological issues. In Lake Tondano, Sholichin and Prayogo (2021) showed that the dominance of agricultural land contributed to a decline in water quality and an increase in lake eutrophication. In the Paguyaman sub-watershed (2022), the distribution of sedimentation was mapped, revealing that most areas had very low sedimentation levels, although some steep zones exhibited high sedimentation potential.

Drought issues are a focus in the Limboto and Bone watersheds, where Ayuba et al. (2018) and Ayuba (2018) used SWAT to identify vulnerability to drought. The results indicate that certain areas are classified as vulnerable; however, implementing appropriate land use scenarios can significantly mitigate this vulnerability.

Overall, these findings highlight the crucial role of SWAT in elucidating the dynamics of water quality, sedimentation, and water availability and support more adaptive and sustainable watershed management.

Southeast Sulawesi

Research in southeast Sulawesi mainly focuses on two studies that use the SWAT model to analyze the impact of land cover change. In the Wanggu watershed, Hariyanto et al. (2024) demonstrate that land conversion to agriculture and settlements increases sedimentation, particularly in the upstream areas, but this can be mitigated through conservation scenarios. Meanwhile, Yasidi et al. (2023) in the Lasolo watershed found that mining and deforestation caused fluctuations in runoff and sedimentation, with a downward trend in recent years, owing to land rehabilitation.

West Sulawesi

In west Sulawesi, Muhammad Agung et al. (2018) studied the potential for micro-hydro energy development in the Bonehau watershed using the SWAT model. The results showed that the spatial planning scenario was able to produce higher water discharge and electrical power compared to actual conditions, while also contributing to erosion control and river flow stabilization. This study emphasizes the importance of integrating land use and hydrological modeling to support renewable energy development in remote areas.

Overall, the reviewed literature suggests that SWAT applications are unevenly distributed, with south Sulawesi being the most prominent, while central Sulawesi remains understudied, despite its ecological vulnerability. This imbalance highlights the need for more balanced, interdisciplinary, and spatially comprehensive research across Sulawesi.

THE SWAT MODEL IN EROSION AND SEDIMENTATION STUDIES

Application of the SWAT model in Sulawesi

Sulawesi Island is the third most prolific region in terms of SWAT publications in Indonesia after Java and Sumatra, the end of 2021 (Ikhwali et al., 2022) (Figure 2). The highest concentration was found in south Sulawesi, particularly in the Mamasa, Jeneberang, and Bila watersheds. Other studies were conducted in north Sulawesi, Gorontalo, southeast Sulawesi, and west Sulawesi. Over time, this number continues to grow, with various follow-up studies emerging from 2022 to 2024.

Research on the use of the SWAT model in Sulawesi shows uneven spatial distribution, with the highest concentration in south Sulawesi. Many studies have been conducted in the Mamasa, Jeneberang, and Bila watersheds, which have high land cover dynamics and relatively adequate spatial data. In other provinces, SWAT studies have been conducted in southeast Sulawesi (Wanggu and Lasolo watersheds), west Sulawesi (Bonehau), and the north Sulawesi–Gorontalo region (Lake Tondano, Limboto, Bone, and Paguyaman). Meanwhile, no SWAT studies have been found to have been conducted in central Sulawesi, despite the region's high topographical and ecological vulnerability to erosion and sedimentation. This indicates an important research gap that needs to be addressed to support equitable and comprehensive watershed management in Sulawesi. Tables 1–4 are intended as a descriptive synthesis of the literature used.

Purposes of SWAT applications in Sulawesi

The reviewed studies show that SWAT has been applied in Sulawesi for different research objectives. In general, the use of the SWAT model in Sulawesi covers five main goals:

1) Analysis of the impact of land cover change

Studies in the Mamasa, Jeneberang, and Bila watersheds show that the conversion of forests to agricultural land or settlements has an impact on increased soil erosion and surface runoff. The SWAT model is used to map erosion spatially and project its impact on river discharge and water quality.

2) Conservation and spatial planning scenario simulations

In the Karajae, Tanralili, and Lisu watersheds, the model was used to evaluate forest conservation scenarios compared to intensive agriculture. The simulation results showed that conservation approaches such as reforestation and agroforestry were effective in reducing sedimentation and stabilizing flow.

3) Evaluation of water availability and baseflow

In the Maros and Bone watersheds and lake areas such as Tondano and Limboto, SWAT was used to model baseflow fluctuations, which are important for water security, irrigation, and lake ecosystem conservation, particularly in the context of seasonal climate change.

4) Assessment of micro-hydro energy potential (PLTMH)

The SWAT model was used in the Bonehau and Kelara watersheds to estimate river discharge as a basis for sustainable energy planning

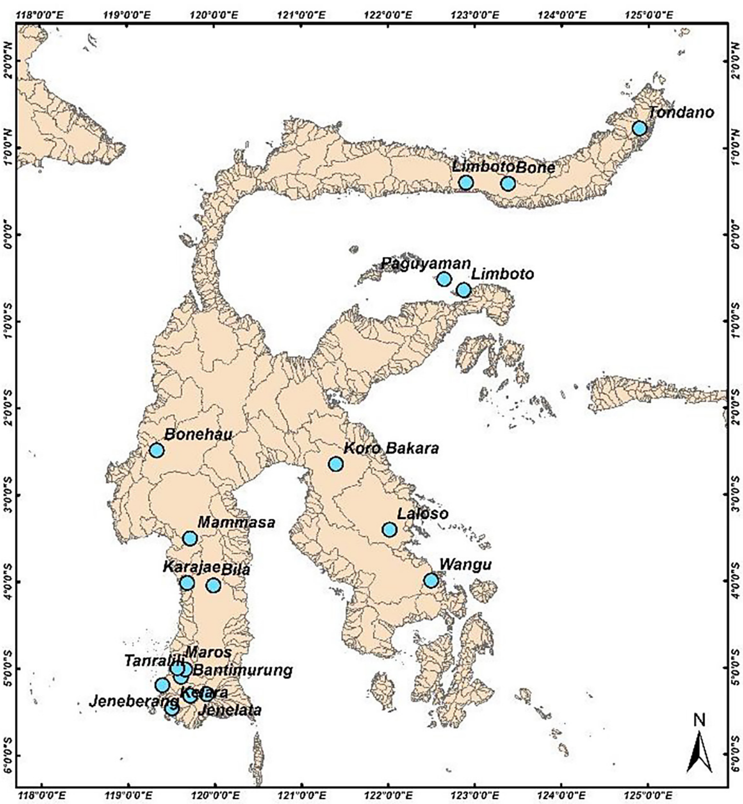

Figure 2. Location of the SWAT model application study in the Sulawesi region

Table 1. SWAT-based erosion and sedimentation studies in South Sulawesi

Researcher name	Location of the watershed	Focus of study	Output	Weaknesses
Murtilaksono et al., 2017	Mamasa Watershed	Land conservation and use scenarios	Conservation scenarios significantly reduce runoff and sedimentation	No calibration was performed because the DAS was classified as unmeasurable.
Anila et al., 2020		RTRW and conservation impacts	Spatial planning scenarios reduce erosion and sedimentation	No calibration or validation of the model was performed.
Irlan et al., 2023		River discharge and flow trends	The SWAT model shows an increase in discharge from upstream to downstream.	Weak calibration due to limited data and parameters
Isra et al., 2023	Sub-watershed of Mamasa	Spatial distribution of sedimentation	The highest sedimentation was identified in the downstream area	The validation results are not explained in detail
Wahyuni, 2023	Bila Watershed	The impact of land cover change on runoff coefficient	Increase in runoff coefficient	No model validation
Sholichin, 2020		Risk of flooding due to land cover change	Peak discharge simulation	Not yet considering the influence of climate
Putera, 2020	Jeneberang Watershed	Changes in forest cover and their impact on runoff and baseflow	Quantification of changes in runoff and baseflow	The effect of water quality was not analysed.
Fitrian & Boro, 2021	Koro Bakara Watershed	Risk of flooding due to conversion of protected forests	Flood vulnerability map	No model validation
Chairil et al. 2021	Karajae Watershed	Optimisation of land use in conservation scenarios	Evaluation of the impact of conservation scenarios	Spatial approaches are still common
Mandy, 2020	Maros Watershed	Projections of water availability due to land cover change	Projections of changes in water availability	Lack of exploration of causal factors
Surahman et al., 2021	Sub-watershed of Tanralili	The impact of vegetation loss on base flow	Identification of baseflow decline	Not accompanied by a restoration scenario
Samsul, 2019	Lisu Watershed	Comparison of actual conditions and spatial planning	Comparison of land use scenarios	No model validation
Barkey et al., 2019	TN Bantimurung Bulusaraung	Climate projection-based flood simulation	Climate flood risk projections	No policy response
Muis et al., 2020	Kelara Watershed	Evaluation of micro-hydro power plant potential based on spatial planning	Identify potential locations for micro-hydro power plants	Socio-economic aspects were not discussed.
Nursaputra et al., 2021	Jenelata Watershed	The impact of spatial planning on water and carbon emissions	Quantification of water and emission changes	No model validation

Table 2. SWAT-based erosion and sedimentation studies in Southeast Sulawesi

Researcher name	Location of the watershed	Research focus	Output	Weaknesses
Hariyanto et al., 2024	Wanggu Watershed	The impact of land cover change on sedimentation	Evaluation of the effectiveness of vegetative and mechanical conservation	No model validation
Yasidi et al., 2023	Lasolo Watershed	Fluctuations in runoff and sedimentation due to mining and deforestation activities	Identification of spatial-temporal changes in sedimentation	No assessment of water quality impact

Table 3. SWAT-based erosion and sedimentation studies in West Sulawesi

Researcher name	Location of the watershed	Research focus	Output	Weaknesses
Muhammad Agung et al., 2018	Bonehau Watershed	Potential for developing micro-hydro energy based on spatial planning	Identify potential PLTMH locations	Not yet considering socio-economic and technical aspects in the field

Table 4. SWAT-based erosion and sedimentation studies in north Sulawesi and Gorontalo

Researcher name	Location of the watershed	Research focus	Output	Weaknesses
Sholichin and Prayogo, 2021	Tondano Lake	The effect of land cover on lake water quality	Mapping water quality and the impact of land use	Does not examine the role of domestic or industrial waste
Ayuba et al., 2018	Limboto Watershed	Drought vulnerability based on land use scenarios	Spatial mapping of drought vulnerability	No model validation
Ayuba, 2018	Bone Watershed	Spatial analysis of drought vulnerability	Drought risk zoning	No alternative risk reduction solutions have been modelled yet
Eska Zuhriana Adam, 2023	Sub-watershed of Paguyaman	Spatial estimation of sedimentation rates using SWAT and GIS	Mapping of priority zones for sedimentation control	Does not include long-term hydrological influences or climate change

in remote areas. These findings confirm the flexibility of SWAT in supporting the development of renewable energy based on local resources.

5) Flood risk and extreme rainfall simulation

In the Jeneberang watershed and conservation areas such as Bantimurung-Bulusaraung National Park, models are used to simulate peak discharge and flood-affected areas based on intensive rainfall scenarios, which is useful for disaster mitigation and regional planning.

SWAT analysis data

The SWAT model requires spatial and climatological input data to simulate hydrological dynamics, erosion, and sedimentation in a watershed. On the basis of a review of studies analyzed in Sulawesi, there are generally four main types of data used, namely topography, land cover, soil, and climate data. All four play an important role in determining the accuracy of simulation results, but also face implementation challenges in the field.

1. Topographic data

Topographic data is used to establish watershed boundaries, determine flow direction, slope gradient, and flow length, parameters that greatly influence runoff calculations and erosion potential (Beeson et al., 2014). Almost all studies in Sulawesi, such as those by Isra et al. (2023) in the Mamasa sub-watershed and Chairil et al. (2021) in the Karajae watershed, use a 30-meter resolution Digital Elevation Model (DEM) from SRTM. Although sufficient for medium to large watersheds, this resolution limitation affects the accuracy of delineation in small watersheds or areas with extreme contours (Al-Khafaji et al., 2020).

2. Land use/land cover data

Soil erosion by water is a major factor in land degradation and affects the quality of urban watershed areas, while land use and surface cover play a key role in controlling the rate of soil loss and surface runoff (Baja et al., 2014). Land cover information is crucial for determining important variables such as rainfall interception, evapotranspiration, and erosion coefficients (Al-Khafaji et al., 2020). Studies by Murtilaksono et al. (2017) and Anila et al. (2020) in the Mamasa watershed, as well as Fitrian and Boro (2021) in the Koro Bakara watershed, used Landsat satellite imagery and RTRW maps to describe the dynamics of land use changes. However, some publications did not mention the year of the imagery or the classification method, as seen in the study by Samsul (2019), raising doubts about the representation of actual conditions (Pai and Saraswat, 2013).

3. Soil data

Soil data influences parameters such as infiltration, available water capacity (AWC), and erodibility. Generally, data is obtained from national soil maps, FAO Soil Maps, or SoilGrids. A study by Barkey et al. (2019) in the Bantimurung-Bulusaraung National Park area utilized global-scale soil data due to limitations in local data. Meanwhile, Muis et al. (2020) in the Kelara watershed combined soil data with local measurements to evaluate micro-hydro energy potential. External studies, such as Ngeang et al. (2019), showed that FAO data produced better outputs than SoilGrids in flow and sedimentation simulations in the Yom watershed, Thailand, due to the suitability of input parameters to the SWAT structure.

4. Climate data

Daily rainfall data and other climate elements are important inputs that drive the simulation process in the model. Wahyuni (2023) in the Bila watershed and Hariyanto et al. (2024) in the Wanggu watershed used data from BMKG and NASA POWER to fill climatological data gaps in the study areas. The greatest challenge is the limited distribution of rainfall stations, which causes data gaps in remote watersheds. Some studies, such as those by Yasidi et al. (2023) in the Lasolo watershed, rely on gridded data such as CHIRPS and TRMM, which have coarser spatial resolution and do not always capture local variations well (Leta et al., 2018). In addition to the four main types of data, a number of studies also use other supporting data such as river discharge (e.g., by Irlan et al., 2023), RTRW maps for scenario evaluation (Samsul, 2019), and field observations for actual erosion calculations and model calibration (Nursaputra et al., 2021). The use of this combination of data plays an important role in improving the accuracy of simulations and the relevance of results for conservation decision-making and watershed planning.

Influence of watershed scale

The size of a watershed is an important factor that influences the structure of the SWAT model, spatial resolution, and complexity of analysis. In Sulawesi, studies show that watershed scale directly influences the number of sub-watersheds and HRUs (hydrologic response units) formed, as well as the sensitivity of results to data input quality.

In large-scale watersheds such as Mamasa, Jeneberang, and Lasolo, SWAT enables comprehensive spatial analysis covering various land use variations and biophysical characteristics. Studies in the Mamasa watershed by Murtilaksono et al. (2017) and Anila et al. (2020) utilized this model to evaluate broad land conservation scenarios, producing detailed spatial distributions of sedimentation, including the identification of critical downstream areas. Meanwhile, Yasidi et al. (2023) successfully mapped the impact of mining activities in the Lasolo watershed on erosion and sedimentation patterns over a long period of time. The large area provides an advantage in analyzing cross-district scenarios and in capturing the complexity of ecosystems.

Conversely, in medium to small watersheds such as the Mamasa sub-watershed (Isra et al., 2023), Tanralili (Surahman et al., 2021), and Paguyaman (Maroddin et al., 2022), the SWAT model was used to capture local dynamics in greater detail. However, simulations in small watersheds are more susceptible to inaccuracies in input data, such as DEM or land cover. For example, in the Mamasa sub-watershed, the model showed high sedimentation in the downstream area (> 1.400 tonnes/ha/year), which formed the basis for determining priority conservation zones. Meanwhile, the study in the Paguyaman sub-watershed produced a spatial classification of sedimentation vulnerability levels to support zoning-based control.

The watershed scale also affects the number of HRUs and the complexity of modeling. Large watersheds tend to produce more HRUs, providing flexibility in analysis but increasing computational load. Conversely, small watersheds produce limited HRUs but allow for more focused and contextual conservation simulations.

Thus, the selection of the watershed scale must be tailored to the research objectives. Large watersheds are more appropriate for strategic analysis and cross-administrative boundary management, while small watersheds and sub-watersheds are more ideal for micro-conservation testing, erosion zoning, and local land use impact assessment.

Weaknesses of the SWAT analysis in Sulawesi

In addition to the challenges related to the quality and resolution of input data, a number of methodological weaknesses also hinder the optimal use of the SWAT model in Sulawesi. One of the main weaknesses is inconsistency in model calibration and validation procedures. Some studies do not include statistical performance tests (e.g., NSE or R^2) or only mention manual calibration without explaining the parameters used. The absence of validation procedures makes it difficult to assess the reliability of the simulation results presented. Another weakness is the lack of scenario development. Most studies only model actual conditions, without developing scenarios for changes in land use, climate, or conservation. In fact, the main strength of SWAT lies in its ability to evaluate the impact of scenarios on hydrological systems and erosion processes. As a result, the analysis results tend to be descriptive and do not support policy-based decision making. Furthermore, most SWAT studies in Sulawesi also lack integration of socio-economic and spatial aspects, such as population data, community land use patterns, or zoning regulations. The dominance of technical-physical approaches without institutional linkages makes simulation results less contextual in their application in the field.

From a spatial perspective, there is an imbalance in the distribution of research, with most studies concentrated in south Sulawesi. To date, no SWAT studies have been found in central Sulawesi, even though the region has high ecological vulnerability due to high rainfall, steep topography, and massive land use change. Overall, the challenges in implementing the SWAT in Sulawesi are not only related to limited input data, but also concern aspects of the approach, scenario development, cross-sector integration, and distribution of research areas. Therefore, it is necessary to strengthen SWAT studies that are interdisciplinary, applicable, and cover all provinces in Sulawesi more evenly to support sustainable watershed management.

Overall, the literature review indicates that SWAT has been widely applied in Sulawesi for various purposes, including flood risk assessment, water availability analysis, conservation scenarios, land cover change evaluation, and micro-hydro energy potential assessment. Applications are still uneven, though, with the majority of research focused on south Sulawesi and little on central Sulawesi. Recurring challenges include methodological problems such as uneven calibration and validation, inadequate scenario development, and limited socioeconomic integration.

CONCLUSIONS

The SWAT model has become a relevant and flexible tool for analyzing erosion and sedimentation dynamics in the Sulawesi region. This study shows that most research has focused on south Sulawesi province, with a predominance of studies in the Mamasa, Jeneberang, and Bila watersheds. The application of SWAT in Sulawesi has covered various needs, such as land use change simulation, conservation evaluation, flood modeling, and micro-hydro energy potential estimation.

However, there are still a number of weaknesses in the application of the model, including inconsistent calibration and validation procedures, limited use of scenarios, and low integration with socio-economic and spatial dimensions. In addition, there are geographical disparities in the distribution of research, with areas such as central Sulawesi not covered at all.

Considering the existing potential and challenges, it is necessary to develop a more comprehensive, interdisciplinary, and adaptive SWAT modeling approach tailored to local conditions. This effort is crucial to ensure that the use of SWAT can truly contribute to sustainable and evidence-based watershed planning and management across the entire Sulawesi region.

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