

Water, land, and food: A swat-based approach to sustainable resource management in Tanralili Sub-Watershed South Sulawesi

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ABSTRACT

The sustainable management of water, land, and food resources is crucial for food security in areas under environmental stress. This study focuses on the Tanralili Sub-Watershed in South Sulawesi, Indonesia, which faces soil erosion, water imbalance, and land degradation. The Soil and Water Assessment Tool (SWAT) was integrated with a geographic information system (GIS) to assess hydrological responses to land use dynamics and their impact on agricultural productivity. Spatial data, including a 2023 land use map, digital elevation model, soil parameters, and climate data, were processed for hydrological simulation. Model calibration and validation were performed using observed streamflow data to ensure accuracy. The results show high erosion rates ($>3000 \text{ t.ha}^{-1}$) and runoff in sub-watersheds with steep slopes and intensive farming, whereas forested areas demonstrated better infiltration and reduced sediment yield. Conservation strategies, such as reforestation, terracing, and water harvesting, were identified to improve irrigation efficiency by up to 20%. Integrated resource management is projected to enhance water availability, reduce land degradation, and support sustainable food production. These findings provide a scientific basis for policy and demonstrate the relevance of SWAT modelling in watershed management.

Keywords:

Food security, Soil erosion, SWAT, Watershed management, Water resources

1. Introduction

Managing natural resources, such as water, land, and food, within the Tanralili Sub-Watershed in South Sulawesi poses significant challenges that are deeply intertwined with environmental and socioeconomic factors. This region, like many others in Indonesia, is affected by climate change, leading to issues such as flooding, landslides, soil erosion, and drought. Deforestation and forest fragmentation further exacerbate these challenges, significantly impacting biodiversity and ecosystem services [1,2].

Land degradation, primarily driven by erosion, is a critical issue that affects food security and livelihoods, particularly in humid tropical areas. This environmental degradation necessitates prioritisation in watershed management because of constrained budgets and the extensive area requiring restoration [2]. In response, integrated watershed management (IWM) has been promoted as a strategic approach to mitigate the impacts of climate change. This involves collaboration across various levels of government and communities, emphasising the revival of traditional knowledge in conjunction with modern scientific approaches [3].

The Tanralili Sub-Watershed is a crucial area because of its environmental sensitivity and socio-economic importance. The integration of local wisdom and scientific



methods helps ensure sustainable management practices. This dual approach not only addresses immediate environmental concerns but also supports the socio-economic well-being of local communities, many of whom are dependent on forest resources for their livelihoods [4].

Sustainable resource management in watershed areas, such as Tanralili, is vital for preventing land degradation and ensuring the long-term health of ecosystems and the communities that rely on them. Continuous policy development, implementation of conservation techniques, and research support these efforts, which aim to significantly reduce the area of degraded land. Effective management requires a comprehensive understanding of the area's ecological, economic, and social dynamics, highlighting the importance of participatory approaches that involve all stakeholders [5,6].

The Soil and Water Assessment Tool (SWAT) is a comprehensive, process-based hydrological model developed to forecast the effects of land management practices on water, sediment, and agricultural chemical outputs in extensive and intricate watersheds. The primary advantage of SWAT lies in its capacity to simulate the interconnected processes of hydrology, weather, sediment, crop growth, nutrients, pesticides, and agricultural management, rendering it highly relevant for watershed management studies [7].

SWAT is particularly advantageous for integrated resource management because of its capability to handle diverse datasets, such as climate, land cover, soil properties, and management practices, over long-term periods. This model allows researchers to evaluate the effects of climate change and land cover change on streamflow, offering crucial insights for designing water resource structures and planning management strategies at the regional or basin scale [8].

Moreover, SWAT supports the incorporation of traditional knowledge with scientific approaches, as seen in efforts to design integrated watershed management technologies. This integration helps adapt community-based management practices that are feasible and acceptable while ensuring sustainable resource management. Furthermore, the application of SWAT in conjunction with tools such as geographic information systems (GIS) and the analytical hierarchy process (AHP) for prioritizing land restoration demonstrates its versatility in addressing issues of land degradation and supporting decision-makers toward sustainable land resource management in data-scarce regions [9].

The objectives of this study were to apply the SWAT model in the Tanralili Sub-Watershed, assess the impact of land use on hydrology and soil erosion, and identify sustainable management strategies to support food security and resource conservation.

2. Methods

This study was conducted in the Tanralili Sub-Watershed, located in South Sulawesi Province, between 5°00'–5°12' South latitude and 119°34'–119°56' East longitude, with a total area of 27,594 ha. This study was conducted in three main stages. The first stage involved collecting secondary data, including daily climate data (rainfall, maximum and minimum temperature, solar radiation, wind speed, and humidity), a digital elevation model (DEM) with a 30-m resolution, soil data, and a 2023 land use map.

The second stage focused on collecting and analyzing soil samples from the field to provide detailed soil parameters required by the soil and water assessment tool (SWAT) model. The third stage involved the SWAT modelling process, which included several technical sub-stages: (1) watershed delineation using ArcSWAT based on the DEM, (2) HRU analysis based on land use, soil type, and slope class, (3) input and construction of daily climate data formatted into SWAT input files (PCP, TMP, SLR, HMD, and WGN), (4) running the model, (5) model calibration and validation using observed streamflow data, and (6) hydrological simulation to assess water availability and the impact of land use on water and soil resources [10].

The land use map from 2023 served as the sole spatial input for understanding current landscape conditions and their effects on runoff and erosion processes. Spatial analysis was conducted using ArcGIS 10.3, particularly for overlay, classification, and zoning functions, to identify critical areas that contribute significantly to surface runoff and sediment yield. Daily climate data were compiled into SWAT-compatible formats, including PCP (precipitation), TMP (temperature), SLR (solar radiation), HMD (humidity), and WND (wind speed) files for the study area. Soil data were encoded as physical properties, such as effective depth, infiltration rate, field capacity, and available water content [11].

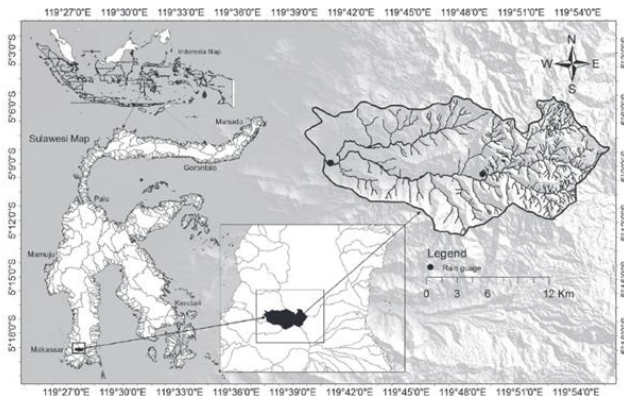


Figure 1. Map of the Tanralili Sub-Watershed [12]

3. Results and Discussion

Results should be clear and concise. The results should summarize (scientific) findings rather than providing data in great detail. Please highlight the differences between your results or findings and those of previous publications by other researchers. The discussion should explore the significance of the research findings and not repeat them. The separation or combination of the Results and Discussion sections is acceptable. Avoid extensive citations and discussions of published literature.

An analysis of the annual average data from 23 sub-watersheds (Sub-DAS) (Table 1) showed that precipitation values in the study area were relatively uniform, ranging from 2,984 to 3,006 mm per year. This stability in rainfall indicates that the region receives a fairly even spatial distribution of rainfall input, allowing consistent hydrological conditions between subregions. However, other components of the water balance, such as percolation and surface runoff, showed significant variations.

For example, Sub DAS 5 and Sub DAS 7 recorded very high surface runoff values of 1,170.9 mm and 1,193.3 mm, respectively. These high values may reflect a low soil infiltration capacity, possibly due to a compacted soil structure, lack of protective vegetation, or steep land slopes. Such conditions can increase the risk of surface erosion and loss of water that should otherwise be absorbed into the ground [13,14].

Table 1. Sub basin of the Tanralili Sub-Watershed

Sub Basin	ha	%
1	1032.02	3.74
2	3644.10	13.21
3	780.11	2.83
4	344.26	1.25
5	307.15	1.11
6	1069.04	3.87
7	1408.70	5.11
8	13.33	0.05
9	645.95	2.34
10	3111.98	11.28
11	2957.40	10.72
12	78.73	0.29
13	1296.98	4.70
14	224.20	0.81
15	489.93	1.78
16	1084.67	3.93
17	192.65	0.70
18	829.68	3.01
19	2745.38	9.95
20	613.73	2.22
21	876.48	3.18
22	2247.97	8.15
23	1599.72	5.80
Total	27594.14	100.00

Table 2. Slope of the Tanralili Sub-Watershed

Slope	ha	%
0-8%	2983.99	10.81
8-15%	2814.98	10.20
15-25%	5518.02	20.00
25-45%	9636.78	34.92
>45%	6640.37	24.06
Total	27594.14	100.00

Table 3. Landuse of the Tanralili Sub-Watershed

Landuse	ha	%
Forest-Mixed	20813.36	75.43
Rice	2848.07	10.32
Agricultural Land-Generic	2413.10	8.74
Water	2.69	0.01
Little Bluestem	1516.93	5.50
Total	27594.14	100.00

Land use significantly affects water and soil resource conditions, especially in watersheds (DAS), with varying topographies (Table 2) and land use intensities (Table 3). Based on land use data, areas covered by mixed forests accounted for approximately 66.01% of the total area. Forest cover plays an important role in regulating water management by increasing rainwater infiltration and absorption and serving as a protective barrier against erosion by strengthening the soil structure through complex root systems [15]. Conversely, land used for rice fields and general agriculture, which comprises approximately 23.6%, shows a higher tendency for surface runoff and sediment production, especially if managed intensively and located in areas with steep slopes [16].

Groundwater availability was indicated by high subsurface water accumulation values. Sub-DAS 4 and Sub-DAS 5 recorded the highest values at 1,108.7 mm and 1,086.7 mm, respectively. These high groundwater values suggest that these two areas have the potential to serve as effective recharge zones, likely supported by porous soil types and sufficient vegetation cover. However, another land quality indicator, sedimentation, showed serious degradation in some areas. Sub-DAS 18 and Sub-DAS 19 experienced extreme sedimentation rates of 4,528.6 and 3,203.6 metric tons.ha⁻¹, respectively. These figures indicate intense erosion, likely caused by unsustainable land management on steep slopes with minimal vegetation cover. This is further

supported by the high lateral flow values in the same Sub-DAS, indicating significant horizontal water loss that can lead to further topsoil loss [17,18].

Based on these evaluation results, Sub-DAS 12, 15, 18, and 19 were identified as priority areas for land and water conservation interventions. These sub-DAS not only showed high sedimentation and lateral flow values but also indicated an imbalance in their water balance, which could impact the overall productivity of the watershed ecosystem. Therefore, implementing conservation measures, such as reforestation, terracing, and the construction of micro dams (check dams), is necessary to control runoff and reduce erosion loads [19].

In addition, a spatial analysis of water balance distribution patterns showed that Sub DAS 13 and 17 had more balanced hydrological characteristics, with high percolation (760.7 and 606.2 mm, respectively) and relatively low surface runoff (790.4 and 828.8 mm, respectively). This indicates that these areas likely have gentler topographies or more stable land use systems. These spatial differences emphasize that topographic variation and land cover type are determining factors in the water balance at the sub-watershed level [20].

Furthermore, a topographical analysis indicates that 59% of the total watershed area has slopes greater than 25%, which are classified as steep or very steep. Farming on steep slopes can drastically accelerate erosion rates if not accompanied by adequate soil conservation measures. This is consistent with previous studies, which state that agricultural intensification on sloping land without conservation treatment is the main cause of soil degradation and a decline in watershed quality [21]. Sub-watersheds 15-19 in the data showed high sediment and runoff values, which are strongly suspected to result from agricultural expansion in areas that are ecologically unsuitable for intensive cultivation [16].

To address this, improved land-use scenarios should be implemented, including agroforestry, terraced farming systems, and slope-adaptive soil and water conservation techniques. Agroforestry not only enhances resistance to erosion but also contributes to diversifying farmers' incomes. In addition, it is important to convert marginal agricultural land on steep slopes into grasslands or community forestry areas that are more suitable for the land's capability. This approach aims to maintain the sustainability of the hydrological functions of the watershed while improving land productivity in the long term [22].

Agricultural practices in the study area were dominated by the use of land for rice fields (13.06%) and general agricultural land (10.52%), which together accounted for approximately 23.6% of the total area of 27,594 ha. This land use pattern demonstrates that the agricultural sector plays a significant role in local food security. However, the average sediment data ($\text{t}\cdot\text{ha}^{-1}$) in several sub-watersheds, such as SUB 18 ($4,528.6 \text{ t}\cdot\text{ha}^{-1}$) and SUB 19 ($3,203.6 \text{ t}\cdot\text{ha}^{-1}$), indicate high rates of soil degradation, most likely caused by cultivation practices that are not adapted to topographical conditions (slope gradients $>25\%$) and minimal implementation of land conservation. Soil erosion can result in the loss of nutrient-rich topsoil, which ultimately leads to a gradual decline in crop yields [23].

Unintegrated water and land management has led to imbalances in the distribution of water yield and its contribution to agricultural productivity. Sub-watersheds with high water yield but low sedimentation, such as SUB 7 (water yield 2,360.4 mm;

sediment 245.3 t.ha⁻¹), demonstrate that good water and vegetation management practices can ensure sustainable agricultural production. Conversely, in sub-watersheds such as SUB 12 and SUB 18, high sediment levels indicate that more rainwater is lost as surface runoff and is, thus, not optimally utilized for irrigation and plant growth. This highlights that efficient water management, such as rainwater harvesting and drip irrigation, has the potential to improve production efficiency and enhance food security [24].

A spatial analysis of slope gradients and land uses revealed that areas with gentle slopes (0–8%), covering 2,984 ha, are highly suitable for agricultural intensification, particularly through the use of precision agriculture technologies and crop rotation. In contrast, areas with steep slopes (>25%, encompassing 16,277 ha or 59% of the area) are better suited for diversification toward agroforestry, perennial crops, or livestock pastures to reduce erosion and enhance the multifunctionality of the land. This approach aligns with the principles of sustainable landscape management by integrating economic productivity and natural resource conservation [25].

Integrated natural resource management has become the main approach for addressing land degradation, declining agricultural productivity, and water availability crises in areas with diverse land uses and topography, such as the studied watershed. One of the main interventions for sustainable water utilization is the application of water conservation technologies, such as the construction of reservoirs, infiltration wells, and retention ponds in sub-watersheds with high surface runoff and low infiltration (e.g., sub-watersheds 5 and 7). In addition, the use of water-efficient irrigation systems, such as drip and sprinkler irrigation, is recommended to enhance the efficiency of agricultural water use [26].

From a land management perspective, an approach based on slope and land use type is required. On steep slopes (>25%), terracing, contour farming, and ground cover vegetation are recommended to reduce the speed of surface runoff and suppress erosion. The rehabilitation of critical lands using locally adapted drought-resistant plants, such as tree legumes and deep-rooted grasses, can also enhance water absorption and improve soil structure [24]. In flat areas with high production potential, the integration of food crops and livestock, as well as the use of organic fertilizers derived from agricultural waste, can increase productivity while maintaining long-term soil quality. To increase food production without sacrificing the environment, crop diversification strategies (such as integrating food and horticultural crops) and the selection of drought-resistant and high-economic-value varieties need to be expanded. Adjusting cropping patterns according to the rainy season and utilizing rainwater through water harvesting systems are key to supporting food security, especially in areas with uneven rainfall distribution. These strategies require a participatory approach involving farmers, the government, and research institutions to ensure the sustainability of watershed management and the productivity of agricultural systems.

4. Conclusion

A SWAT model-based analysis applied to 23 sub-watersheds showed significant spatial variations in the distribution of water balance components, soil erosion, and water yield potential. Although annual precipitation was relatively uniform (~3000

mm) across all sub-regions, different hydrological responses were observed depending on land use and slope. Sub-watersheds 18 and 19 exhibited extremely high erosion rates ($> 3000 \text{ t.ha}^{-1}$), indicating severe land degradation in areas with steep slopes and predominantly poorly managed agricultural land. Conversely, sub-watersheds dominated by mixed forest cover showed higher percolation and groundwater levels, as well as lower sediment yields, reflecting the important role of vegetation in regulating the water cycle and maintaining soil stability. These findings are crucial for sustainable resource management. By identifying critical zones through a spatial approach, interventions can focus on areas that have a significant impact on the quality and quantity of water resources in the future. In addition, the simulation results highlight the need to integrate water, soil, and land use management to achieve long-term environmental resilience and productivity.

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