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Erosion Prediction Using the SWAT Model for Land Use Planning in the Upper Progo Sub Watershed

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Abstract. Research on erosion in the Upper Progo sub watershed is urgently needed to assess the impact of land use changes and to provide land use recommendations that result in lower erosion rates. In this study, we applied the Soil and Water Assessment Tool (SWAT) model. Analysis of erosion data from various land uses in the study area indicated that average erosion rates increased from 95.91 tons/yr in 2018 to 107.17 tons/yr in 2022. Land use changes in the sub watershed have significantly impacted erosion levels, particularly in steep areas that are more susceptible to soil degradation. Poor land management practices have accelerated soil erosion, further exacerbated by the loss of vegetation cover, which making soil particles more prone to detachment and being carried away by water. The proposed land use should prioritize conservation-based management. The simulation results indicate that the recommended land use patterns could significantly reduce average erosion up to 51.34%.

1. Introduction

Soil erosion is an environmental problem in different parts of the world [1]. According to the UNEP (United Nations Environment Program), soil degradation is more than 1,642 million hectares of land were eroded in the world. Water erosion is the most common type among soil degradation processes, accounting for about 55% of the eroded land [2]. Soil erosion is a severe threat to the environment and considered as one of the most serious environmental issues constraining the sustainable development of human society and economies [3]. Soil erosion also brings about off-site damages, such as fluvial sediment deposition, reservoir sedimentation, and channel silting [4]. Improving knowledge of the probable future rates of soil erosion, accelerated by human activity, is important both for policy makers engaged in land use decision-making and for earth-system modelers seeking to reduce uncertainty on global predictions [5].

The Upper Progo sub watershed serves as a conservation and buffer zone but has faced significant damage due to physical changes. These changes are primarily the result of increasing land conversion for agricultural purposes and the development of infrastructure, such as expanding settlements and roads. This has led to erosion and sedimentation in downstream areas. In the Upper Progo sub watershed, local residents primarily engage in tobacco farming during the dry season, while corn and horticultural crops are cultivated during the rainy season. Agricultural and plantation activities cover more than 70% of the total sub watershed area, leaving only 0.4% as forest cover. The ongoing deforestation has caused a substantial decline in vegetation cover. Plantation expansion predominantly occurs in areas with slopes greater than 30%, resulting in significant land degradation, notably through soil erosion [6]. The described changes in land use indicate a disruption to the ecosystem within the Progo Hulu sub watershed, which is crucial as it acts as a buffer zone that impacts downstream areas through sediment transport and the movement of dissolved materials in other water flow systems. [7] conclude that the prediction of future soil erosion can help in the management of valuable cropland and suggest the need for continually changing soil conservation strategies.

Further studies are essential to evaluate the impact of land use changes on erosion rates. This study aims to assess the impact of land use changes on erosion rates across different land uses over two time periods: 2018 and 2022. Additionally, the study examines the development of proposed land use for effective erosion control in the Upper Progo sub watershed.

2. Materials and methods

2.1. Research Location

The Upper Progo Sub watershed is situated in Temanggung Regency, Central Java Province. Geographically, it is located between 7º11'42"–7º22'46" South Latitude and 109º59'44"–110º12'31" East Longitude. According to the automatic delineation results from ArcSWAT, the study site covers an area of 41,316.94 hectares.

2.2. Tools and Materials

Several key factors influence soil erosion processes, including precipitation rates, topography, soil type, and vegetation cover. The Soil and Water Assessment Tool (SWAT) takes these factors into account and can be used to identify areas that are vulnerable to soil erosion, as well as to estimate soil loss, sediment transport, and deposition. This tool is effective for prioritizing areas that require intervention and for evaluating alternative soil management and conservation practices aimed at mitigating erosion [8].

The tools utilized in this study include a laptop, Microsoft Office, ArcGIS 10.8.2, ArcSWAT 10.8.2, SWATCUP, Avenza, SPAW Hydrology software, a camera, stationery, tally sheets, labels, a shovel, a measuring tape, a hoe, soil ring samples, a hammer, and plastic materials.

2.2.1. Data collection

The data used in this research comprises two types: primary and secondary data. Primary data is derived from soil samples collected from the field. These samples are categorized as disturbed and undisturbed. Disturbed soil samples are analyzed to obtain information on soil structure, texture, and organic matter content. In contrast, undisturbed soil samples are utilized to assess soil permeability and bulk density. The secondary data include a Digital Elevation Model (DEM), river network maps, land use maps from 2018 and 2022, slope maps, soil type maps, river discharge data, rainfall data (from 2018 to 2022), and climate data (including minimum and maximum temperatures, wind speed, solar radiation, and relative humidity).

2.2.2. Input data processing

Before entering data into ArcSWAT, it must adhere to specific formatting requirements; therefore, data processing is necessary. This includes processing both climate and soil data. Soil data processing involves entering laboratory analysis results into Microsoft Access, while climate data is processed using the WGEN User software.

2.2.3. Model simulation

The model simulation is conducted in several stages: watershed delineation based on DEM data, the formation of Hydrological Response Units (HRUs) using soil type maps, land use maps, and slope maps, defining climate data, and finally running the model.

2.2.4. Model Calibration and Validation

Calibration is the process of adjusting a set of parameters to enhance the agreement between observed hydrological responses and simulation results. In this study, model calibration was conducted to understand the relationship between river discharge generated by the SWAT model and river discharge based on measured data [9]. Calibration and validation tests were performed using the SWAT-CUP application, specifically the SUFI-2 (Sequential Uncertainty Fitting version 2) algorithm.

Before calibration, it is essential to determine the sensitivity of the calibration parameters using observed discharge data collected from Kranggan Station. The identification of sensitive parameters within a watershed is typically informed by literature reviews or sensitivity analyses. For this study, the selection of parameters for calibration was based on research conducted by [10]. The parameters chosen are those deemed influential in watersheds with tropical characteristics. The statistical criteria employed for assessment are R^2 (coefficient of determination) and NSE (Nash-Sutcliffe Efficiency), which are commonly used methods in the calibration and validation process [11].

During calibration, simulation parameter values are adjusted to ensure that the output closely reflects real-world conditions. In this study, 11 parameters were utilized, as detailed in the table below, followed by the calibration and validation process. The specific sensitive parameters used in the calibration of the Upper Progo Sub watershed include the following: surface flow curve number (CN2), soil evaporation factor (ESCO), deep water percolation fraction (RCHRG_DP), available water capacity in the soil layer (SOL_AWC), groundwater delay time (GW_DELAY), water depth in shallow aquifers (SHALLST), initial groundwater level (GWHT), hydraulic conductivity in the main alluvium channel (CH_K2), average slope length (SLSUBBSN), wet soil density (SOL_BD), and saturated hydraulic conductivity (SOL_K).

2.2.5. Model Development of Land Use Guidelines

Land management implementation scenarios are developed by creating land use change scenarios. These land use guidelines are based on implementation plans designed to reduce erosion in the Upper Progo sub watershed.

3. Result and discussion

3.1. SWAT Model Running and Output

The delineation process resulted in 21 sub basins with a total area of 41,316.94 ha. From these 21 sub basins, 1,518 HRUs were obtained as units of analysis in the SWAT model. HRUs were formed based on overlay maps of soil type, land use, and slope class. The model was run using previously prepared data, namely micro-watershed delineation data, HRU definition data, and climate data. The run was conducted over two time periods: 2018 and 2022. The SWAT model output produced a hydrological cycle occurring in the simulation area. The main processes in the hydrological cycle include evaporation, transpiration, condensation, precipitation, surface and subsurface runoff. Although the total amount of water in the cycle remains constant, its distribution among the various processes is constantly changing, influenced by factors such as watershed surface conditions, slope, land cover, rainfall, rainfall intensity, and rainfall duration. In the hydrological cycle, incoming rainfall is distributed through several pathways: water passing through the plant canopy (through fall), flow along plant stems (stem flow), and rainwater that directly reaches the ground surface. This water is then divided into surface runoff, evaporation, and water that seeps into the soil (infiltration). Runoff and infiltration then flow into rivers and contribute as discharge [12].

Based on the results of the SWAT model, the average precipitation in the Upper Progo Sub watershed was 2,064.05 mm per year in 2018, leading to a surface runoff of 482.93 mm. By 2022, the average precipitation in the same sub-watershed increased to 2,850.35 mm annually, resulting in a surface runoff of 551.51 mm. This difference in runoff between 2018 and 2022, it was 482.93 mm in 2018 compared to 551.51 mm in 2022 can be attributed to changes in land use.

This observation aligns with the research conducted by [1], which concluded that soil erosion is significantly influenced by climate change, particularly through changing precipitation patterns. Additionally, [13] noted that fluctuations in precipitation directly affect soil erosion, impacting factors such as rainfall amount, intensity, and the spatial and temporal distribution of rainfall. The temporal distribution of rainfall often interacts with land use changes.

Land use affects surface runoff in several ways, including reducing the amount of rainwater that reaches the land surface through interception, slowing down surface runoff by enhancing infiltration capacity, and retaining soil moisture on the surface. Thus, vegetation plays a crucial role in minimizing the conversion of rainwater into surface runoff. Changes in land use directly impact overland flow and fluctuations in river flow, as detailed by [14]. A summary of the land use changes in the study area can be found in Table 1.

Table 1. Comparison of Land Use Area in 2018 and 2022

Nu.	Land use type	Area (Ha)				Changes	
		2018	%	2022	%	Ha	%
1	Forest plantation	20,881	50.5	2,312	5.6	18,569.4)	-44.9
2	Shrubs	582	1.4	694	1.7	112.5	0.3
3	Settlements	4,696	11.4	5,751	13.9	1,054.6	2.6
4	Rice fields	13,033	31.5	12,704	30.8	329.1	-0.8
5	Dry land agriculture	100	0.2	8,588	20.8	8,487,4	20.5
6	Mix shrubs and dry land agriculture	2,025	4.9	11,269	27.3	9.244	22.4
	Total	41,317	100	41,317	100	0	0

Source: Data analysis, 2025

3.2. Calibration and Validation

Calibration is the process of adjusting model parameters to ensure that the model simulation results reflect the actual conditions of the area being analyzed. According to [15], the calibration process is necessary to assess the extent to which model output matches observations or field data. Calibration uses 2019 flow rate data for the daily period from January 1 to December 31. Calibration is performed by adjusting sensitive parameters that significantly influence the hydrological process being analyzed. Adjustments to several parameters are made to increase the NSE and R2 values so that they approximate the observed flow rate data. Parameter adjustments are performed manually using a trial and error method [15].

After the calibration process, validation is performed using data not used in the calibration. Validation aims to ensure the consistency of the results of a process according to predetermined specifications. This process is carried out by comparing the calibrated flow rate data with measured flow rate data from different time periods. The parameters used during the validation process remain the same as those used during calibration. The statistical analysis applied is also similar, namely using the coefficient of determination (R^2) and Nash–Sutcliffe Efficiency (NSE). Validation aims to prove and ensure that the calibrated model can provide accurate results in predicting hydrological conditions in different periods. The data required in the validation process is daily flow discharge data from January 1, 2019, to December 31, 2019.

The calibration process consisted of 8 iterations, each involving 1,000 simulations. The results from the calibration test yielded an R^2 value of 0.62, which is considered satisfactory, and a Nash-Sutcliffe Efficiency (NSE) value of 0.58. Following this, validation was conducted, resulting in an R^2 value of 0.62 (also satisfactory) and an NSE value of 0.51.

These findings indicate a correlation between the simulation results and the observed data, suggesting that the model possesses good predictive ability. The R^2 value of 0.62 reflects the strength of the relationship between the simulation results and the observed data, while the NSE values of 0.58 and 0.51 demonstrate the model's accuracy in replicating the observed data and its overall performance. The model falls into the good and satisfactory categories. However, it should be noted that there is a considerable degree of uncertainty present. According to Yang, potential sources of uncertainty include: (1) model simplification, (2) natural processes not accounted for, (3) artificial processes not considered, and (4) input data that inadequately describe the conditions of the watershed.

3.3. Erosion Distribution Estimation Analysis

Various factors influence erosion, including climate (particularly rainfall intensity), topography, soil properties, vegetation cover, and land use [12]. Notably, changes in land use and crop management due to climate change may have a more significant impact on soil erosion than alterations in rainfall or temperature alone [13].

The results of the SWAT model simulations for 2018 and 2022 illustrate the changes in erosion levels within the complex Upper Progo Sub watershed. This simulation aims to assess the impact of land use changes on the extent of erosion. By comparing data from these two years, we can identify changes in the magnitude of erosion along with the factors influencing these changes, thus offering guidance for more sustainable land use practices in the study area. Figure 1 presents a comparison of the erosion rates that occurred in the Upper Progo sub watershed in 2018 and 2022.

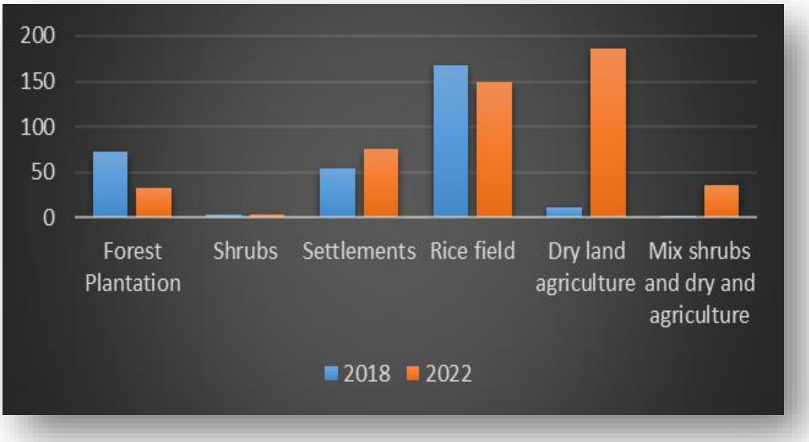

Fig. 1. Graph of Erosion Rates in the Upper Progo sub watershed for 2018 and 2022

The above graph figures that the average erosion rate in the Upper Progo sub watershed was 95.91 tons/ha/year in 2018, which increased to 107.17 tons/ha/year by 2022. The most significant increase in erosion occurred in dryland agriculture, where the erosion rate rose dramatically from 10.54 tons/ha/year to 186.56 tons/ha/year. Most dryland agricultural areas are situated on gentle slopes (8-15%) to very steep slopes (over 40%), which can accelerate surface water flow. This process allows soil particles to be easily transported, resulting in the loss of fertile soil layers and a decrease in soil fertility. Dryland agriculture is primarily utilized for cultivating annual crops such as tobacco, cabbage, carrots, potatoes, and chili peppers.

Additionally, dryland farming mixed with shrubs also experienced a notable rise in erosion, increasing from 2.53 tons/ha/year to 36.19 tons/ha/year. This increase can be attributed to the sparse vegetation, which is less effective at protecting the soil. While dryland farming systems mixed with shrubs generally resist erosion better than pure dryland farming due to the presence of natural vegetation, the diminished density of vegetation and shrubs in these areas diminishes their ability to bind the soil effectively. Consequently, the land cover in dryland farming mixed with shrubs does not fully protect the soil surface, leaving it exposed to raindrops and leading to increased erosion.

Settlements significantly contribute to soil erosion, with rates increasing from 53.61 tons/ha/year to 76.30 tons/ha/year. This rise is primarily due to land conversion, the loss of vegetation, and increasingly compacted soil structures that reduce water absorption and increase surface runoff. The high erosion rates in settled areas are attributed to the prevalence of impermeable surfaces, such as roads and buildings, which prevent rainwater from infiltrating the soil. Consequently, rainwater becomes surface runoff, heightening the potential for erosion. The increase in erosion from 2018 to 2022 is likely linked to the expansion of settled areas and the reduction of natural vegetation that normally acts as a water absorber.

In contrast, plantation forests saw a decrease in erosion, with rates falling from 72.57 tons/ha/year to 32.71 tons/ha/year. This decline is likely due to denser tree growth and improved soil retention. While plantations maintain relatively good vegetation cover, the presence of monoculture trees and insufficient understory growth leaves the soil vulnerable to erosion. The reduction in erosion from 2018 to 2022 can be attributed to increased vegetation density, enhanced root biomass that stabilizes the soil, and the adoption of conservation practices such as agroforestry and layered planting techniques.

Rice paddies also experienced a decrease in erosion, from 167.86 tons/ha/year to 149.67 tons/ha/year, largely due to the implementation of conservation techniques like terracing, which helps reduce surface water flow. However, rice paddies typically face very high levels of erosion because the land is frequently tilled and exposed to irrigation water. Even when fields are planted with crops, issues such as poor irrigation systems or bank erosion can exacerbate soil loss. The modest decrease in erosion may result from improvements in soil conservation practices, such as building more stable rice bunds and utilizing better irrigation systems.

Shrubs have experienced a slight increase in erosion, rising from 2.88 tons per hectare per year to 3.47 tons per hectare per year. This increase is attributed to disturbed vegetation and shallow root systems, which make these areas less effective at retaining soil. Compared to plantation forests, shrubs have lower canopy cover and shallower roots. The rise in erosion rates is likely due to the degradation of shrub vegetation caused by natural disturbances or human activities, such as land clearing for agriculture or residential development. The SWAT simulation results indicate moderate erosion estimates; however, the model may not account for water infiltration accurately, suggesting that actual erosion rates could be higher than estimated.

Additionally, soil characteristics that contain high levels of dust (ranging from 20% to 55%) contribute to increased erosion rates, as dust is easily dislodged and transported by water flow. Since the industrial revolution, climate change has been driven by the emission of greenhouse gases and rapid economic and technological development. The climate changes affecting soil erosion primarily include alterations in temperature and precipitation patterns.

3.4. Proposed Land Use Scenario for Erosion Control

This land use scenario was developed with consideration for the spatial planning patterns of Temanggung Regency. The proposed land use was then simulated using the SWAT program, which allows for the adjustment of land use through the HRU Definition feature in the Land Use Refinement menu. Below is a description of the land use guidance for the Upper Progo sub watershed, based on the spatial planning patterns of Temanggung Regency.

Table 2. Land use recommendations

Land unit	Erosion level	Proposed land use
Rice field (RICE)	Moderate	Horticulture Limited forest production Plantations Settlements
Dry land agriculture (AGRR)	High	Crops Horticulture Settlements Plantations Limited forest production Protected forest
Forest plantations (FRSE)	Low	Protected forest Limited forest production Permanent forest production
Settlements (URMD)	Moderate	Limited forest production Permanent forest production Horticulture Settlements Plantations
Mix shrubs and dry land agriculture (HAY)	Low	Plantations Permanent forest production Crops Settlements Horticulture
Protected forest shrubs (RNGB)	Very low	Protected forest Limited forest production Permanent forest production

Table 3. Erosion Rate changes

Land use		Erosion rates (ton/ha/year)	Average (ton/ha/year)
Existing	Forest plantations	32.71	107.17
	Shrubs	3.47	
	Settlements	76.30	
	Rice fields	149.67	
	Dry land agriculture	186.56	
	Mix shrubs and dry land agriculture	36.19	
Recommended	Horticulture	83.50	51.71
	Limited forest production	12.00	
	Plantations	12.21	
	Settlements	8.29	
	Crops	95.07	
	Protected forest	0.36	
	Permanent forest production	24.54	

Based on the data presented in Table 2, various land uses in the area such as rice paddies, dryland agriculture, plantation forests, settlements, dryland agriculture interspersed with shrubs, and scrubland have been transformed into horticulture, food crops, plantations, settlements, limited production forests, permanent production forests, and protected forests. The notable differences in erosion rates before and after implementing the land use scenario are illustrated in Table 3.

Implementing the land use scenario led to a significant reduction in the average erosion rate. Specifically, erosion decreased by 51.34%, dropping from an average of 107.17 tons/ha/year to 51.71 tons/ha/year.

4. Conclusions

The average erosion rate in the Upper Progo Sub-watershed increased from 95.91 tons per hectare per year in 2018 to 107.17 tons per hectare per year in 2022. Dryland agriculture saw the highest increase in erosion, reaching 176.02 tons per hectare per year. In contrast, erosion in plantation forests decreased by 39.85 tons per hectare per year.

Land use changes significantly impact erosion, primarily due to the conversion of forested areas to non-forest lands such as dryland agriculture, rice fields, and settlements. This transformation accelerates soil degradation, increases the risk of flooding and landslides, and exacerbates water runoff.

To mitigate erosion, it is recommended to adopt conservation-based land use practices. These include horticultural agriculture, limited production forests, protected forests, plantations, and food agriculture. Simulation results indicate that implementing these practices can reduce the average erosion rate by 51.34%, lowering it from 107.17 tons per hectare per year to 51.71 tons per hectare per year.

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