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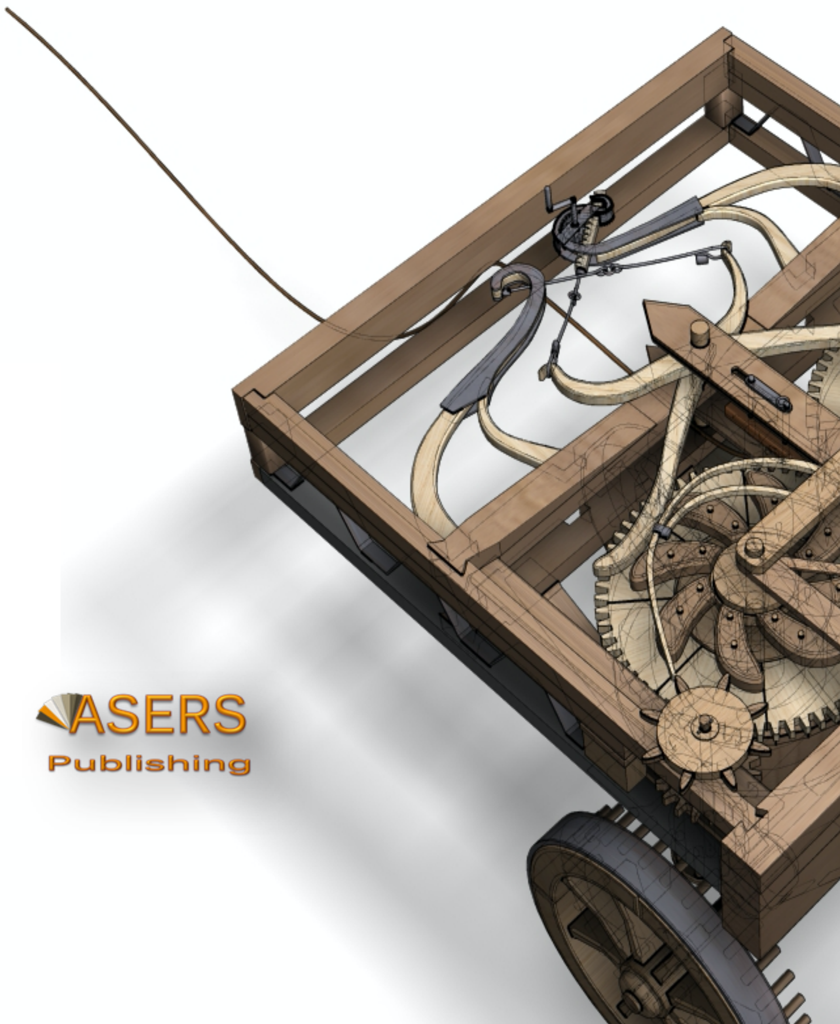

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Table of Contents:

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Journal of Environmental Management and Tourism

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Utilization of Multitemporal Land Cover Data and GIS for SWAT-Based Sedimentation and Runoff Modeling in the Lasolo Watershed, Indonesia

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Abstract:

Sedimentation and surface runoff are two vital processes occurring in a watershed, and calculating the constituent transports of sediments and surface water is the initial step in planning. This research was intended to model surface runoff and sedimentation temporally (2008, 2013, 2018, and 2021) on hydrological response unit (HRU) and subwatershed levels for the Lasolo Watershed in Southeast Sulawesi, Indonesia. Soil and Water Assessment Tool (SWAT), a physically based hydrological modeling instrument, was selected for the simulation using these input data: SRTM DEM, land cover, soil type, and several climatological data sourced from ERA5, NASA GLDAS, and the NASA POWER Project. Results showed fluctuating surface runoff and sediment yield throughout the simulation time frame. The mean surface runoff peaked at a capacity of 216.6 mm/year in 2013, and the mean sediment yield was also the highest this year, 10.8 tonnes/ha/year. In 2021, there was a significant reduction to 18.2 mm/year for surface runoff and 0.91 tonnes/ha/year for sediment yield. Simulations suggested that the watershed's surface runoff capacity is directly proportional to the sediment yield produced.

Keywords: sediment yield; surface runoff; Lasolo Watershed; SWAT.

JEL Classification: Q57; C60.

Introduction

1. Research Background

A series of sedimentation processes in a watershed and the rivers traversing it play central roles in the geomorphological dynamics of the watershed ecosystem (Hadian and Mosaedi 2021). It suggests that both assessment and observation are crucial to studying the fluvial dynamics and management of a watershed (Principe and Blanco 2012;Peterson *et al.* 2018). Lee and Oda (2013) broke down the sedimentation process into three stages: (1) flocculation is the initial stage that produces what is called a floc, (2) deposition then occurs when the flocs settle down gradually, lose water content, and form sedimentary layers, and (3) consolidation refers to the accumulated sediments stabilizing or cementing until an equilibrium state is reached (Lee and Oda 2019). It is imperative that the quantity of sediment transferred be known so as to support various analyses related to water resources, including water quality, freshwater availability, and urban water mechanisms (de Oliveira Fagundes *et al.* 2020; Umugwaneza *et al.* 2022). Sedimentation may affect water quality and change its usability status for various purposes, from consumption to industries, which makes structured monitoring fundamental for identifying the spatial distribution of sediment concentration (Firdausy and Sudaryatno 2017). Dynamic sediment transfers from floodplains are indicated as determinative of watershed management and ecologically relevant to watersheds. The reason is that contaminants like heavy metals, microorganic pollutants, and radionuclides can be easily adsorbed and carried by sediments (Middelkoop and Van der perk 1998; Green 2013).

In line with the perception expressed by Lee & Oda (2019), sediment transport into estuaries generally involves two interrelated physical processes: sedimentation and consolidation, where a number of suspended particles are deposited and cemented (Chauchat *et al.* 2013; Regmi 2021). Soils eroded due to inland activities (Shafaie *et al.* 2015) flow into river channels and then reservoirs (Wagh & Manekar 2021), which store water supply, provide irrigation services, and control floods (Foteh *et al.* 2018). Coarse-sized materials are generally trapped upstream of reservoirs, while finer grains are carried further down to estuaries. These sediments usually cause ecological damage or imbalance (Wagh & Manekar 2021). Sedimentation processes are commonly influenced by causal factors, which are spatially and temporally dynamic (Liu & Jiang 2019).

Land-cover conversion associated with the anthropogenic occupation is empirically responsible for high erosion and sedimentation rates in a watershed. In several cases, losses due to erosion can be difficult to identify because of the combinations of factors, such as topographic features, land use, climate, and human activities (Schmalz *et al.* 2015; Salsabilla & Kusratmoko 2017), and potentially harmful to land productivity (Gull & Dar, 2020). Changes in land cover can have severe implications for the hydrological and ecological aspects of the entire catchment area. Anthropogenic behavior, deforestation, and land conversion are among the factors that shape a watershed's hydrological and response characteristics (Worku *et al.* 2017). Commercial sectors encroach on forests or primary vegetation areas to provide more usable space, which triggers erosion (Ayana *et al.* 2012). These cases are also found in the Lasolo Watershed. Lasolo administratively is part of North Konawe Regency, Southeast Sulawesi, Indonesia, where land is extensively converted to nickel mining sites, and substantial impacts on water quality have been reported. A recent study on one of the rivers in the Lasolo Watershed system by Abry (2022) gives a general picture of the impact, *i.e.*, most water quality parameters (DO, COD, ammonia, phosphate, nitrate, and phenols) in several locations close to nickel mining sites are substandard and show indications of mild pollution.

In the past few years, there has been a massive growth in erosion and sedimentation studies hinging on remote sensing data and geographic information system (GIS) approaches (Mohamed *et al.* 2018; Liu & Jiang 2019; Kuti & Ewemoje 2021). Among the strong reasons is that remote sensing is perceived as the most effective and efficient method to obtain information from the Earth’s surface (Song *et al.* 2011). While knowledge of the spatial distribution patterns and quantitative factors of erosion and sediment discharge can be used to measure their impact on the soil surface and water bodies, most of the supporting data, such as hydrological network density, measurement frequency, and type of constituent, are difficult to acquire (Schmalz *et al.* 2015). Several GIS-based tools developed for quantifying erosion and sedimentation are the modified Universal Soil Loss Equation (MUSLE), revised USLE (RUSLE) (Liu & Jiang 2019), Areal Non-point Source Watershed Environment Response Simulation (ANSWERS), Agricultural Non-Point Source Pollution (AGNPS), Water Erosion Prediction Project (WEPP), SHETRAN (Gull & Dar 2020), and Soil and Water Assessment Tool (SWAT) (Salsabilla & Kusratmoko 2017). This research specifically used SWAT as the platform for erosion and sedimentation modeling. SWAT is a physically based hydrological model for estimating the regionally distributed impact of land utilization on air, sediment, and chemical aspects resulting from agricultural practices in a watershed with varied soil land covers (Jain *et al.* 2010; Rahman *et al.* 2016; Zalaki-badil *et al.* 2017; Kuti & Ewemoje 2021). This semi-distributed model is a development of the previous CREAMS and USLE (Neitsch *et al.* 2011). It has the capacity to simulate on the smallest scale (*i.e.*, hydrological response unit) within a short time frame (Arsyad 2010). In the modeling process, SWAT breaks down a watershed or subwatershed into several smaller parts connected by a river network. These smaller parts are called hydrological response units (HRUs), the narrowest unit where all the hydrological processes are simulated. The simulation processes are largely divided into two: land components (movement of water, nutrients, pesticides, and sediments into the river) and river components (movement of water in the channel into the river and then the watershed outlet) (Fohrer *et al.* 2005).

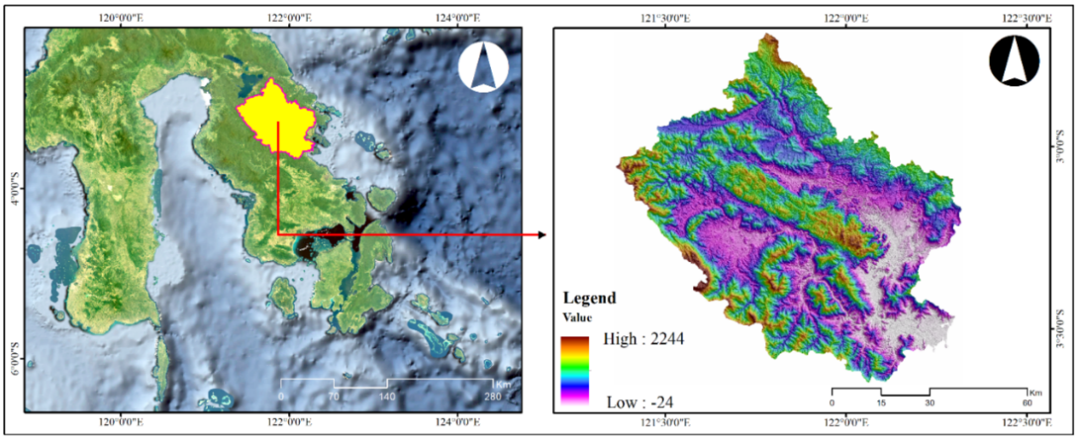
The SWAT concept illustrates rainwater that falls to the ground in an amount that exceeds the infiltration rate and thus forms surface runoff as an agent of erosion and sedimentation (Swami and Kulkarni 2016). Considering the massive conversion of land cover as a result of anthropogenic activities, the Lasolo Watershed is susceptible to erosion and sedimentation. Therefore, the main objective of this research was to model surface runoff and sedimentation temporally for the years 2008, 2013, 2018 and 2021 using SWAT (with predictions made at the HRU level) and MUSLE approaches.

2. Material and Methods

2.1 Study Site

The Lasolo Watershed administratively lies in the North Konawe Regency, Province of Southeast Sulawesi, Indonesia. Astronomically, it spans from 121°46'43.9" to 122°6'33" E and from 2°41'25" to 3°38'46.97" S, which geographically stretches from north to south. The watershed covers an area of 14,979.6 km^2, and the Lasolo River has a total length of 847.2 km (Spatial Plan Document for the North Konawe Regency, 2012–2016) (see Figure 1).

Figure 1. Research location: The Lasolo Watershed presented in color gradations of the SRTM DEM data

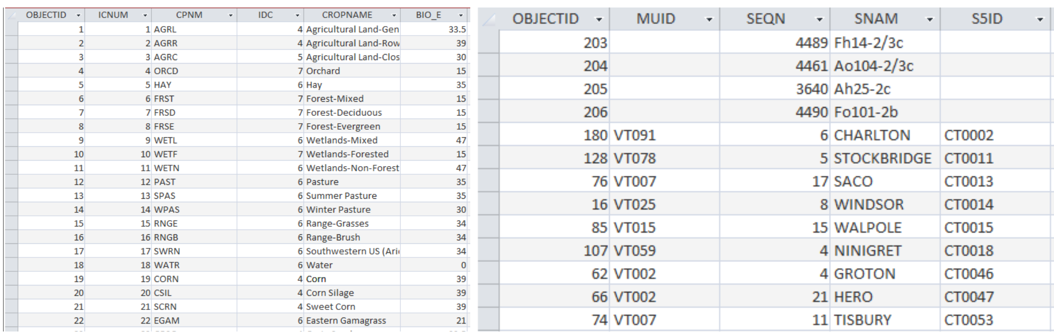


Source: Data Processing

2.2 Input Data and Model Database

This research used GIS-based software, SWAT, and watershed models containing various physical information and was supported by other computing devices.

Figure 2. Screen captures of the SWAT database system for land use (left) and soil types (right), modified and adjusted to the FAO classification



OBJECTID	ICNUM	CPNM	IDC	CROPNAME	BIO_E
1	1	AGRL	4	Agricultural Land-Gen	33.5
2	2	AGRR	4	Agricultural Land-Row	39
3	3	AGRC	5	Agricultural Land-Clos	30
4	4	ORCD	7	Orchard	15
5	5	HAY	6	Hay	35
6	6	FRST	7	Forest-Mixed	15
7	7	FRSD	7	Forest-Deciduous	15
8	8	FRSE	7	Forest-Evergreen	15
9	9	WETL	6	Wetlands-Mixed	47
10	10	WETF	7	Wetlands-Forested	15
11	11	WETN	6	Wetlands-Non-Forest	47
12	12	PAST	6	Pasture	35
13	13	SPAS	6	Summer Pasture	35
14	14	WPAS	6	Winter Pasture	30
15	15	RNGE	6	Range-Grasses	34
16	16	RNGB	6	Range-Brush	34
17	17	SWRN	6	Southwestern US (Ari	34
18	18	WATR	6	Water	0
19	19	CORN	4	Corn	39
20	20	CSIL	4	Corn Silage	39
21	21	SCRN	4	Sweet Corn	39
22	22	EGAM	6	Eastern Gamagrass	21

OBJECTID	MUID	SEQN	SNAM	S5ID
203		4489	Fh14-2/3c	
204		4461	Ao104-2/3c	
205		3640	Ah25-2c	
206		4490	Fo101-2b	
180	VT091	6	CHARLTON	CT0002
128	VT078	5	STOCKBRIDGE	CT0011
76	VT007	17	SACO	CT0013
16	VT025	8	WINDSOR	CT0014
85	VT015	15	WALPOLE	CT0015
107	VT059	4	NINIGRET	CT0018
62	VT002	4	GROTON	CT0046
66	VT002	21	HERO	CT0047
74	VT007	11	TISBURY	CT0053

Source: SWAT database

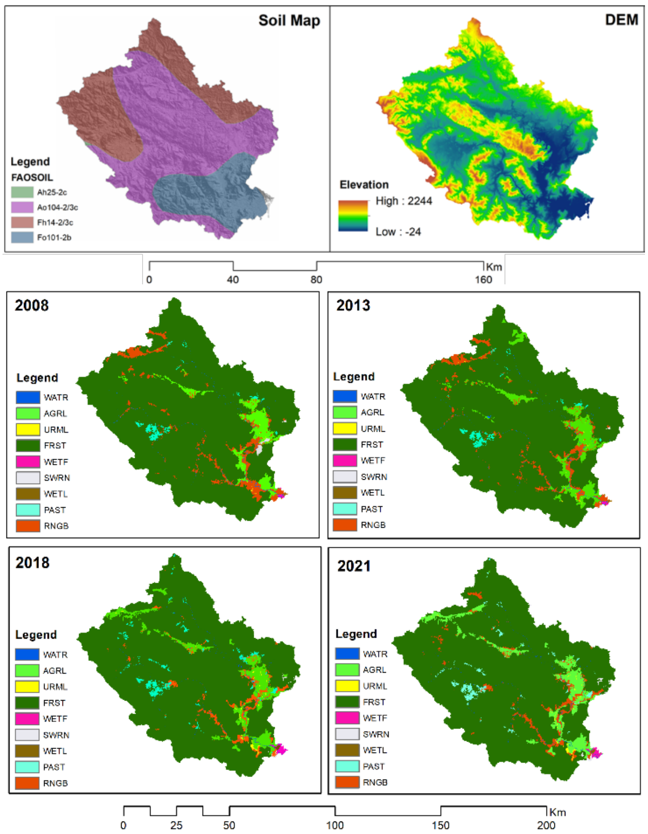
The SWAT computations were performed based on the watershed's physical model; therefore, the data needed were digital elevation models (DEM), river networks, digital soil maps, digital land use maps, and climatological and hydrological characteristics of the Lasolo Watershed. The watershed's main outlet is at the mouth of the Lasolo River, which is at 3°33'13.8"S, 122°16'13.3"E. The entire scheme run in SWAT was stored in the

SWAT2012 Microsoft Access Database. In this database system, all provisions regarding the codes and naming of land use and soil types and the information contained therein were determined. Because the soil type classification referred to FAO, additional input into the SWAT database was needed (see Figure 2).

2.3 Data Preparation and Management

The research database contained several data to be inputted as parameters into SWAT-based modeling, namely DEM, soil type, and land use type across the Lasolo Watershed (see Figure 3), which were obtained from different sources (see Table 1 for details). The DEM data used for the analysis of the study area were SRTM (Shuttle Radar Topography Mission) downloaded from the USGS website (https://earthexplorer.usgs.gov/) with a spatial resolution of 1 arc-second (30 m) in the Georeferenced Tagged Image File Format (GeoTIFF). GeoTIFF is a file type capable of embedding geographic information within it and is thus generally used in numerous applications in the GIS field, especially those operating raster-based.

Figure 3. Input parameters, including soil type, DEM, and land cover



Source: Data Processing

Table 1. Input data for the SWAT modeling of the Lasolo Watershed

No	Input Data	Description	Source
1	Digital Elevation Model	SRTM with a 1-arc-second (30-meter) resolution	USGS
2	Land cover	Land cover data in 2008, 2013, 2018, and 2021	Digital Interpretation of Landsat 7 and Landsat 8, combined with PlanetScope
3	Meteorological data	Rainfall Max-Min temperature Relative humidity Wind speed Solar radiation	ERA5 Daily Aggregates - Latest Climate Reanalysis Produced by ECMWF, NASA GLDAS-2.1: Global Land Data Assimilation System (GLDAS), POWER project by NASA
4	Soil type	-	FAO

Source: Data processing

Relevant parameters like flow accumulation, flow direction, and slopes were derived from the SRTM DEM data. Land use is a physical parameter that influences the amount of runoff, evapotranspiration, and surface erosion within a watershed (Abebe & Gebremariam 2019). Land cover data were obtained by interpreting multi-temporal satellite images in 2008, 2013, 2018, and 2021. The multi-temporal data series allows the research to determine the effect of land-use change on surface runoff and the sediment produced while considering meteorological and hydrological factors.

SWAT modeling has its own database specifications for the inputted land cover classes; therefore, the land cover extraction was adjusted to these standards, which vary by map scale. This adjustment was also applied to the vector soil map to determine the hydrological parameters for each simulated soil type. The different physical and chemical soil properties provide essential information for SWAT models, including soil texture, water content, hydraulic conductivity, and organic carbon content in every soil layer (Abebe & Gebremariam 2019).

2.4 Meteorological and Hydrological Data Input

The current hydrological characteristics run with SWAT for the Lasolo Watershed were studied and simulated using hydrometeorological data. Meteorological data, *i.e.*, rainfall, were derived from analyzing three sets of data: ERA5 Daily Aggregates (the latest climate reanalysis produced by ECMWF), NASA GLDAS-2.1, and the POWER project by NASA. The acquired data were daily rainfall summarized for the modeled years. In addition, temperature data consisting of daily lowest and highest temperatures and wind speed data were extracted from their respective sources (see Table 1) and NASA GLDAS-2.1 using the Google Earth Engine tool by executing a program code (Figure 4 for the screen capture). Finally, relative humidity and solar radiation data were extracted from NASA's POWER project.

Figure 4. Screen capture of the syntax run in the Google Search Engine for temperature data acquisition

```
TEMP_MAX_MIN *
Imports (1 entry)
  var DAS: Table users/agungk213/DAS_LASOLO

var startDate = ee.Date('2008-01-01');
var endDate = ee.Date('2021-12-31');

Map.centerObject(DAS, 10);

var dataset = ee.ImageCollection("NASA/GLDAS/V021/NOAH/G025/T3H")
  .select('Tair_f_inst')
  .filterDate(startDate, endDate);

var list_dataset = dataset.toList(dataset.size());

print(list_dataset);
```

Source: Data processing

2.5 Setting Up the Model Data

The runoff and sediment yield models of the Lasolo Watershed were run on GIS software using the SWAT feature. Arnold *et al.* (1998) described SWAT as a concept and/or operation-based model that runs over a predefined time frame. The development of SWAT-based models aims to predict the implications of management decisions on waters, sedimentation, and agricultural chemicals in a broad watershed area. To obtain maximum results, Arnold *et al.* (1998) suggested designing a model that (a) does not require calibrations considering the large size of the modeled watershed, (b) inputs data that can cover a wide area, (c) uses a computing device capable of processing large data, and (d) enables a long and sustainable period of simulation to calculate the effects of a change in management. In addition, it is imperative that the model to run has the same data projection to avoid systematic errors in the inputted data, which in this research were DEM, land cover, soil type, and other hydrometeorological data. According to Abebe & Gebremariam (2019), the first stage of SWAT modeling is delineating the watershed(s) and subwatershed(s) to be simulated and determining river networks. It is then followed by separating the main watershed into subwatersheds by factoring in the concepts and characteristics of flow direction and accumulation, then dividing the subwatersheds further into hydrological response units (HRUs). In this case, each HRU combined homogenous soil type with land use and slope characteristics. The water balance equation below (see Eq.2.1) was used in the hydrological model to simulate the cyclic movement of water in nature, which is regulated by the hydrologic cycle:

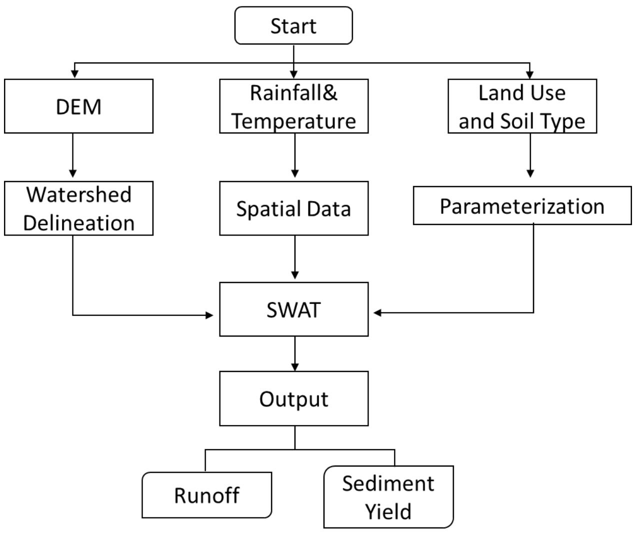
$$SW_t = SW_0 + \sum_{i=1}^{t}(R_{day} - Q_{surf} - E_a - W_{seep} - Q_{gw}) \quad 2.1$$

where SW_t is soil water content (mm), SW_0 denotes initial soil water content (mm), R_{day} represents rainfall (mm), Q_{surf} is surface runoff (mm), W_{seep} is the inflow of water to the vadose zone (mm), Q_{gw} formulates the return flow (mm), E_a is evapotranspiration (mm), and t is time (Arnold *et al.* 1998; Abebe & Gebremariam 2019). The volume of the surface runoff was predicted from daily rainfall; then, the SWAT model estimated the peak discharge using the relevant equation approach, which was modified for each HRU. SWAT also simulated the sediment yield of each HRU by taking into account rainfall and surface runoff using the MUSLE approach (Abebe & Gebremariam 2019), as mathematically expressed below:

$$Sed_i = 11.8(Q_{surf} \times q_{peak} \times A_{hru})^{0.56} \times K_{USLE} \times C_{USLE} \times P_{USLE} \times LS_{USLE} \times CFGR \quad 2.2$$

where **Sed** denotes the sediment yielded (tonne/day), q_{peak} is peak discharge (m^3/s), A_{hru} is the area of the hydrological response unit (HRU, expressed in ha), K_{USLE} is the soil erodibility factor, C_{USLE} is the factor calculated as the effect of land use and cover, P_{USLE} represents the support practice factor, LS_{USLE} is the elevation factor, CFGR denotes the field factor, and 11.8 is the conversion factor (Abebe & Gebremariam 2019). Figure 5 shows the framework of data acquisition for sedimentation and surface runoff modeling using four input data: DEM, land cover, meteorological data, and soil data.

Figure 5. SWAT modeling framework run for the Lasolo Watershed from 2008 to 2021



Source: Data processing

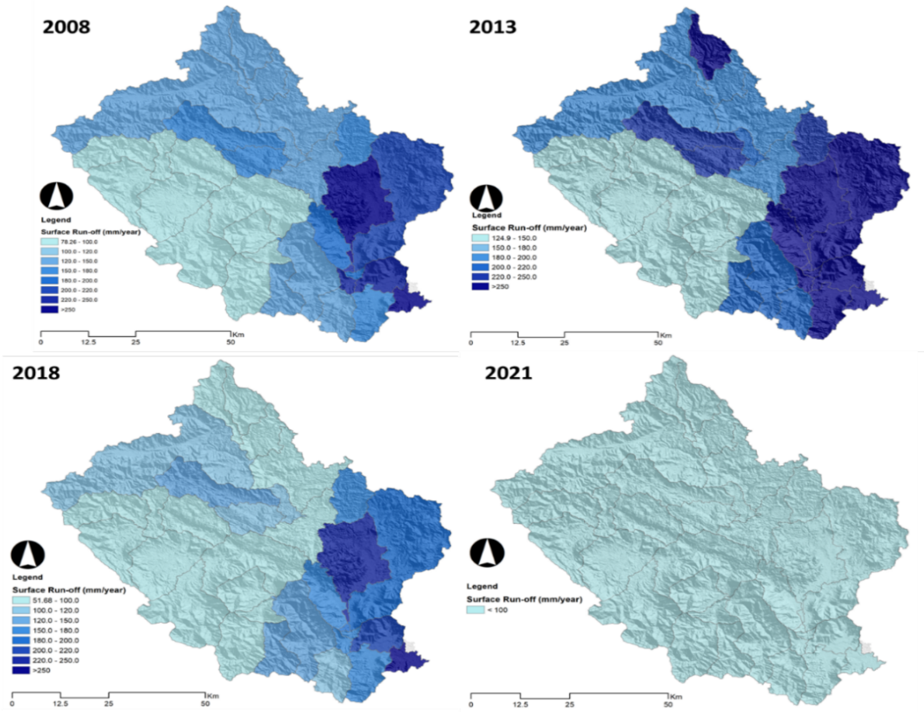
3. Simulation Results for 2008, 2013, 2018, and 2021

The ArcGIS extension for SWAT, *i.e.*, ArcSWAT, was used to quantitatively simulate runoff volume and sediment yield of the Lasolo Watershed. The simulation was run for 2008, 2013, 2018, and 2021. Unlike the common SWAT model, which is a simultaneous model run for several years using one land use map, this research inputted different land use maps for each simulation year. However, to create comparisons, it also ran a general simulation using the data from 2018 to 2020 and the 2021 land cover data obtained from the image interpretation. The model was run on 965 HRUs and 33 subwatersheds (see Figure 6 for the subwatershed's naming), with a total area of 5,849.28 km^2. In addition to land use/cover, the inputted data were daily rainfall, rainfall (ERA5 ECMWF), maximum and minimum daily temperature (ERA5 ECMWF), relative humidity (POWER Project by NASA), wind speed (NASA GLDAS), and solar radiation (POWER Project by NASA). The simulation results showed that, in 2008, the surface runoff of the Lasolo Watershed was, on average, 145.03 mm/year and peaked at more than 278 mm/year in Subwatersheds 22 and 33. In 2013, the mean surface runoff increased to 216.6 mm/year, with the highest total runoff identified in Subwatersheds 21, 22, 24, 25, 27, 29, 31, 32, and 33. This upward trend, however, turned and descended in 2018 to an average of 117.3 mm/year, which was lower than the previous two simulation periods. In this year, the highest surface runoff was detected in Subwatershed 33 or at the outlet of the Lasolo watershed. Then, in 2021, there was a significant decrease in the surface runoff of the entire watershed to <100 mm/year, with an average of 18.2 mm/year (see Figure 7).

Figure 6. Subwatersheds of the Lasolo Watershed

Source: Data processing

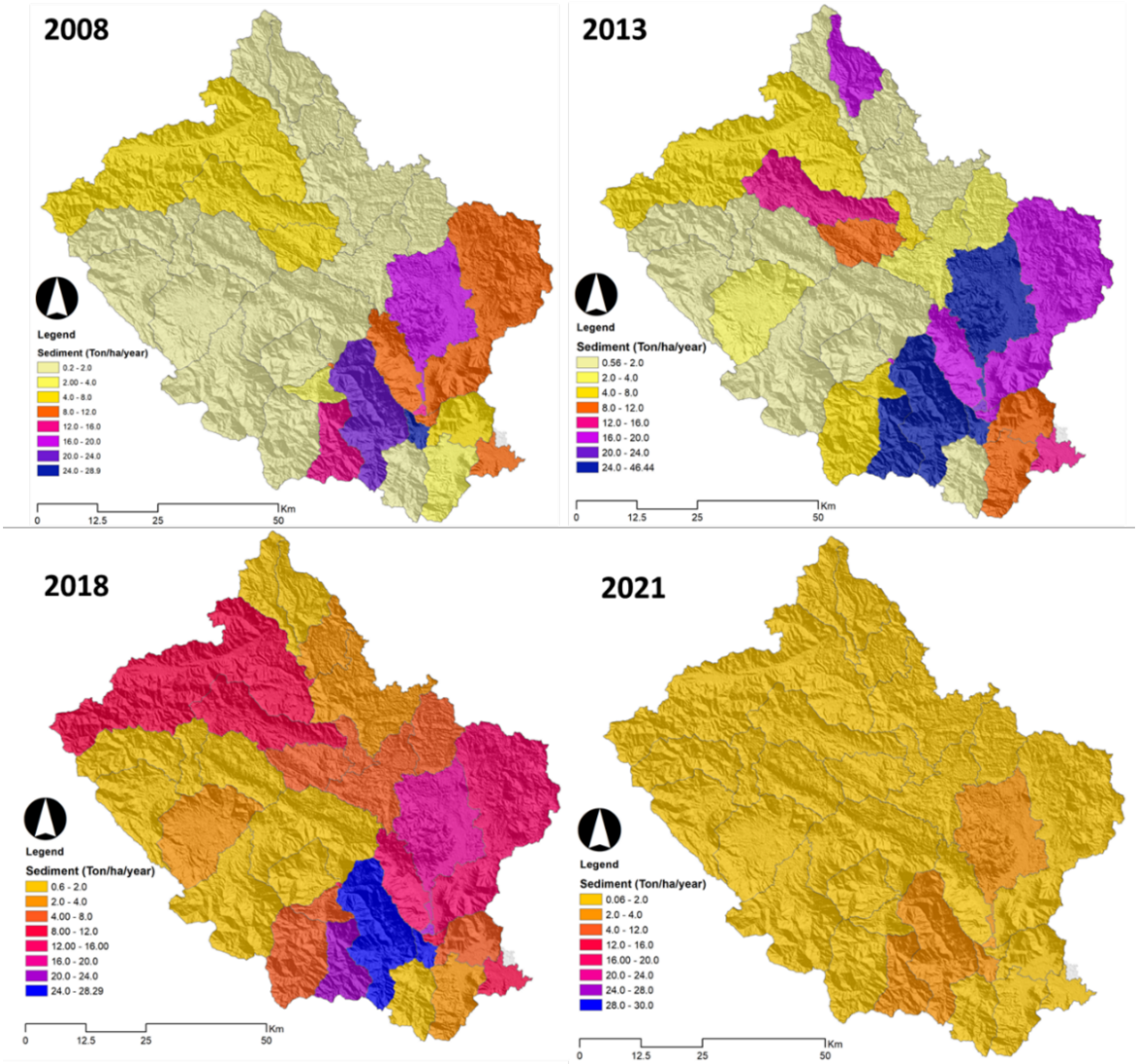
Figure 7. Surface runoff simulation results in 2008, 2013, 2018, and 2021



Source: Data processing

Sediment concentration turns into an important topic of discussion once the pattern of surface runoff is known. The amount of sediment loads or yields produced depends on the runoff volume and the meteorological and physical characteristics of the watershed itself. In watersheds with unique characteristics, specific considerations are placed on rainfall depth and intensity, which may contribute to the detachment and removal of soil particles and infiltration rates that create sediment-rich runoff (Mohammad *et al.* 2016). Based on the model simulated with SWAT (see Figure 8), in 2008, the sediment yield was, on average, 5.8 tonne/ha/year and peaked at 28.9 tonne/ha/year, which was detected in Subwatershed 29. A significant increase started to appear in the 2013 simulation, where the mean sediment yield was 10.8 tonne/ha/year, with the highest total yield reaching 46.44 tonne/ha/year in Subwatersheds 22, 23, and 28. Then, in 2018, a downward trend similar to the surface runoff was observed, where the mean sediment yield decreased to 7.8 tonne/ha/year and the highest total yield to 28.29 tonne/ha/year in Subwatersheds 28 and 29. Although the simulation results generally showed a decreasing trend from 2013 to 2018, there was a substantial increase in sediment yield in the upper course of the Lasolo Watershed. In 2021, the pattern showed a significant decline in sediment yield, where most parts of the watershed area produced < 2 tonne/ha/year, and a few others reached < 4 tonne/ha/year, with an average of 0.91 tonne/ha/year.

Figure 8. Sediment yield simulation results for the years 2008, 2013, 2018, and 2021



Source: Data processing

Figure 9. Relationship between surface runoff and sediment load

Source: Data processing

From the simulations run throughout the time frame, it can be inferred that the surface runoff capacity is directly proportional to the generated sediment load (see Figure 9). The 2013 simulation showed the highest mean surface runoff of 216.6 mm/year and, proportionately, the highest mean sediment yield of 10.8 tonne/ha/year. In contrast, the 2021 simulation indicated the lowest estimate for both surface runoff, 18.2 mm/year, and sediment yield, 0.91 tonne/ha/year. Based on the pattern analysis of the relationship between surface runoff and sediment load (see Figure 9), the surface runoff peaked in 2013.

Conclusions

This study specifically used Soil And Water Assessment Tool (SWAT) to obtain a systematic model to multi-temporally describe sediment concentration and surface runoff discharge in a watershed. The SWAT simulation results indicated a fluctuating pattern throughout the years of observation (*i.e.*, 2008, 2013, 2018, 2021). In 2013, the mean surface runoff and sediment yield were the highest, 216.6 mm/year and 10.8 tonne/ha/year. Then, both decreased until the end of the simulation time frame, where the most significant reduction was observed in 2021. In this year, the mean surface runoff was 18.2 mm/year, and the sediment yield was only 0.91 tonne/ha/year. From these simulations, it can be inferred that the surface runoff capacity is positively related to the sediment produced: the higher the surface runoff is, the more the sediment yield will be generated.

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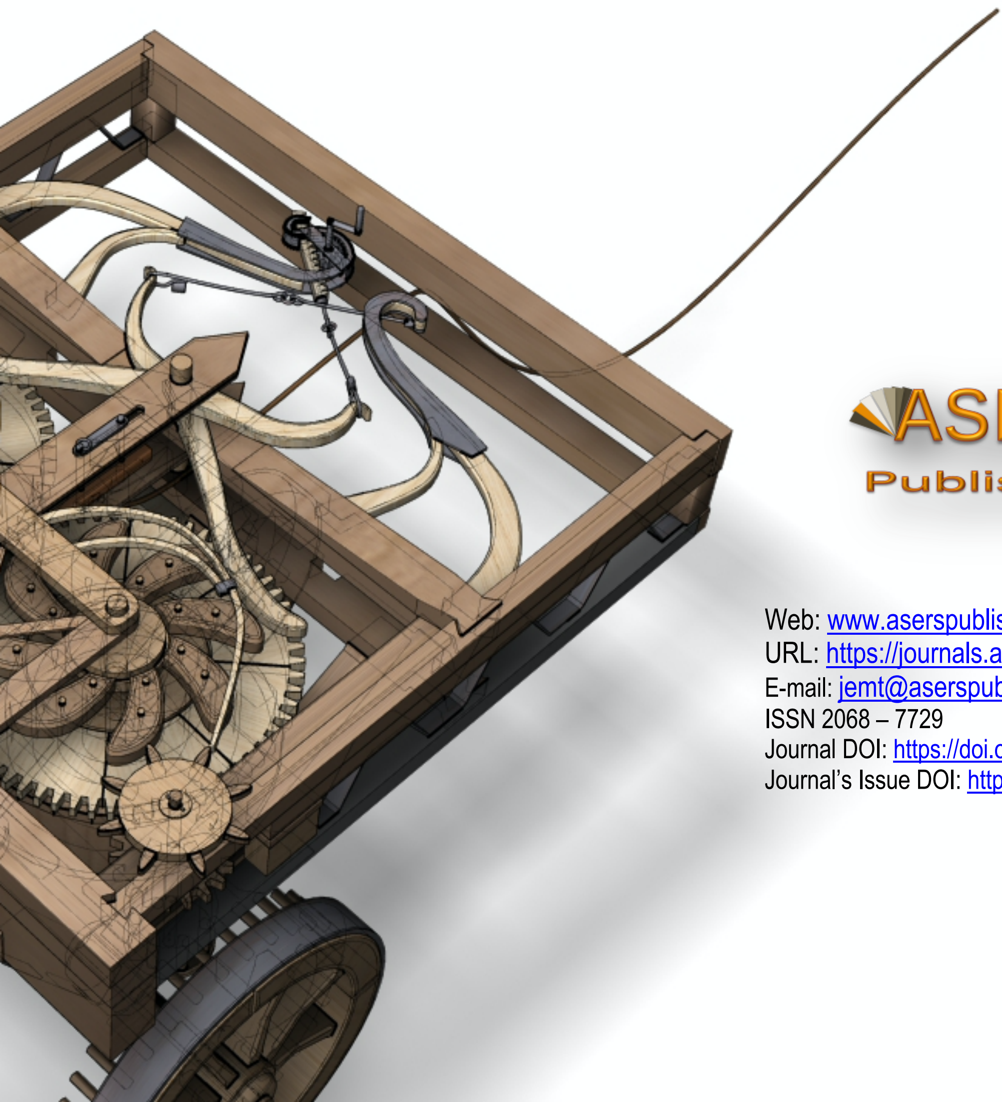

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