Simulating and Predicting Sediment Yield Responses to Land Use Land Cover (LULC) Changes at a Mining Site, Utilizing Geographic Information System (GIS) and Soil and Water Assessment Tool (SWAT)

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Simulating and Predicting Sediment Yield Responses to Land Use Land Cover (LULC) Changes at a Mining Site, Utilizing Geographic Information System (GIS) and Soil and Water Assessment Tool (SWAT)

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Abstract: *Mining operations in the Tagana-an Nickel Project (TNP) have significantly contributed to the country's economy. However, like many mining projects worldwide, TNP has faced numerous criticisms and challenges, particularly regarding sedimentation and its adverse environmental impacts. To address these concerns, the integration of GIS and the Soil and Water Assessment Tool (SWAT) hydrological model proves essential. GIS offers advanced spatial modeling and analysis capabilities, making it an ideal tool for sedimentation assessment. Meanwhile, SWAT enables sophisticated simulation of hydrological processes within a watershed. Among the simulated data, the year 2012 recorded the lowest mean sediment yield at 69.44 tons/ha, followed by 2015, 2018, and 2021 with yields of 89.21 tons/ha, 92.63 tons/ha, and 155.22 tons/ha, respectively. The increasing trend in sediment yield over time is attributed to changes in land use, watershed contour and aspect-slope, mining practices, and natural phenomena such as typhoons.*

Keywords: *Geographic Information System (GIS), Soil and Water Assessment Tool (SWAT) hydrological model, Sediment Yield*

1. INTRODUCTION

Accumulation of sedimentation and alteration in water yield stand out as significant adverse consequences of mining activities. According to Coleta et al. [1], sedimentation is an intricate phenomenon wherein soil particles are eroded and conveyed by moving water or alternative transport mediums, ultimately settling as solid particle layers in bodies of water like rivers and reservoirs. This process is complex and contingent on watershed sediment yield, transportation rate, and deposition mode. Thus, it is important to consider assessing sediment and yield transport to some mining areas to provide up to date data to the mine site operators.

1.1 Statement of the Problem

The Tagana-an Nickel Project (TNP) by Hinatuan Mining Corporation (HMC) has brought notable economic benefits but also raised serious environmental concerns, particularly related to increased sedimentation. Heavy rainfall often causes settling ponds to overflow, reducing their effectiveness and leading to higher water turbidity, contamination, and harm to aquatic life. These issues also diminish the ponds' capacity to manage wastewater. As a result, thorough sedimentation assessments and targeted management strategies are essential to mitigate the project's environmental impact.

1.2 Objectives of the Study

The primary objective of this study was to assess sediment yield in the TNP operated by HMC. Specifically, the study aimed to: (1) generate essential parameter maps for SWAT simulation, including Digital Elevation Model (DEM), slope, and soil maps; (2) develop Land Use Land Cover (LULC) maps for the years 2013, 2015, 2018, and 2021; (3) estimate sediment yield using ArcGIS and the SWAT hydrological model and produce sediment yield maps for 2012, 2015, 2018, and 2021; and (4) analyze the interrelationships among LULC, rainfall, streamflow, and sediment yield within the TNP area.

2. METHODOLOGY

2.1 Study Area

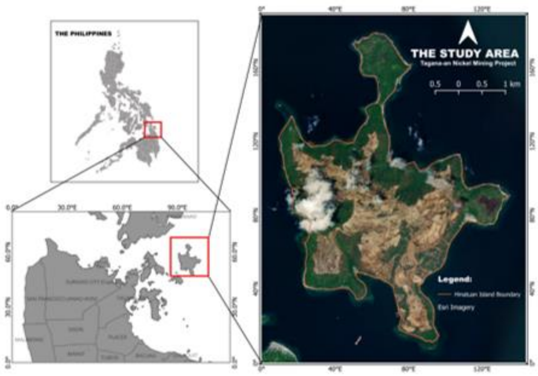

Fig. 1. Location of the study are source: Google Earth, 2023.

Figure 1 shows the TNP of HMC, located on Hinatuan Island in Brgy. Talavera, Tagana-an, Surigao del Norte, Philippines. The site lies within the Surigao Mineral Reservation and spans approximately 1,275 hectares, about 23 kilometers east of Surigao City. It experiences a Type II climate, with an average annual precipitation of

114.01 mm. January is the wettest month (271.43 mm), while May is the driest (48.72 mm).

2.2 Conceptual Framework of the Study

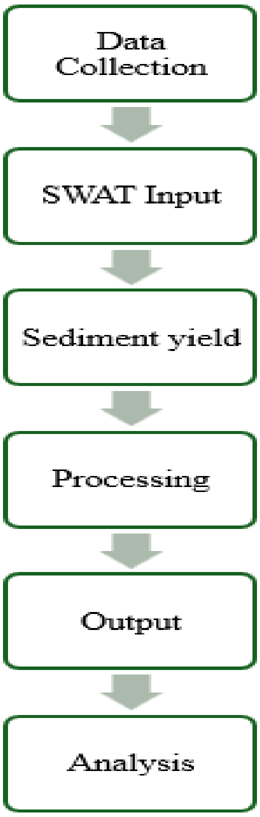

Fig. 2 The conceptual framework of the study

Figure 2 presents the methodological framework of the study, utilizing the SWAT model like the method of Bocobo et al. [2], with some modifications, to analyze sediment and water yield in Hinatuan Island. The process begins with setting the study objectives, followed by collecting essential data inputs needed for the model simulation. These inputs help define the watershed's physical and environmental characteristics. The SWAT model then processes this data to simulate hydrological and water quality conditions. Finally, the analysis phase interprets the simulation results to draw conclusions and provide insights into the sediment and water yield within the watershed.

2.3 Data Sets

The study utilized various data sources, summarized in Table 1. The Digital Elevation Model (DEM) was derived from Interferometric Synthetic Aperture Radar (IFSAR), a high-resolution terrain mapping tool that minimizes errors for accurate analysis. Precipitation data came from the Hinatuan Mining Corporation Meteorological Precipitation Observatory (HMC-MPO), while daily temperature data were sourced from Weather Underground. Land use data for Hinatuan Island were obtained from Copernicus at a 30 m resolution, and the soil map was downloaded from the Harmonized World Soil Database v1.2 by the FAO. The datasets include type of data, spatial resolution used, temporal resolution, and data sources. These datasets were fundamental in assessing the desired analysis.

Table 1. Datasets to be used for simulation in SWAT Model.

Data Type	Description	Spatial Resolution	Temporal Resolution	Data Source
Topography Map	DEM	10 m X 10 m		CCGEO (Caraga Center for Geo-Informatics).
Land Use Map	Land use classification	10 m X 10 m	2021	Copernicus https://www.copernicus.eu
Soil Map	Soil Types	30 m X 30 m	2012	Harmonized World Soil Database v 1.2 Global Soil data: http://www.fao.org/
Meteorological data	Gridded Daily Rainfall	1 degree	Daily 2011-2022	Hinatuan Mining Corporation Meteorological Precipitation Observatory (HMC-MPO)
Meteorological data	Temperature	1 degree	Daily 2011-2022	Weather Underground https://www.wunderground.com/
Hydrological data	Observed stream flow	7 stations	Monthly 2023-2024	HMC
Sediment Data	Observed TSS	7 stations	Monthly 2023-2024	HMC

2.4 SWAT Output

Sedimentation is the process by which eroded soil is deposited into waters. Sediment that accumulates on the bottom of streams and rivers smothers aquatic insects that fish feed upon and buries fish habitat that is vital to reproduction. Sediment filling rivers and streams decreases their storage volume and increases the frequency of floods [4]. The Modified Universal Soil Loss Equation (MUSLE) assists in predicting sediment yield by incorporating inputs such as DEM, soil, land use/land cover (LULC), and weather data, including temperature and daily precipitation. The model determines the sediment budget and runoff through its hydrology component. Sediment estimation in the MUSLE model is a nonlinear function of HRU area [5]. At the HRU level, simulations are performed and summarized at each sub-watershed.

3. RESULTS AND DISCUSSION

3.2 Contour and Aspect-Slope

It is essential to precisely evaluate the watershed area since it holds significance for various purposes, such as hydrologic modeling and habitat preservation. These changes may have a particularly significant impact on the overall shape of the river basin, in particular in mining regions where environmental conditions are constantly changing. Moreover, stakeholders engaged in land management decisions can gain advantages from a well-defined understanding of the watershed's area, allowing them to make informed decisions about land management practices within its limits.

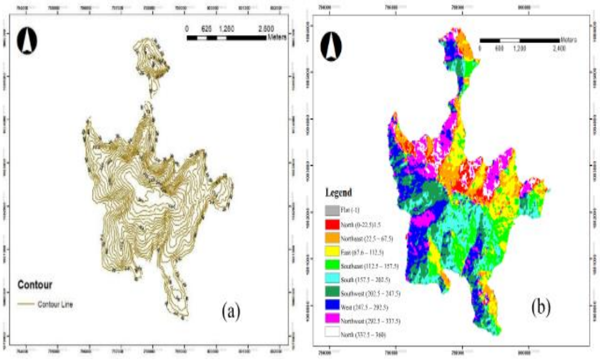

Fig. 3 Contour (a) and Aspect-Slope (b) of study area.

The contour and aspect-slope maps (Fig. 3) play a crucial role in understanding sedimentation and hydrological processes in the study area. Contour lines represent elevation and terrain shape, affecting water flow direction and velocity, which in turn influences sediment transport and deposition. The aspect-slope map illustrates slope steepness and orientation, which impact factors such as solar radiation, temperature, vegetation growth, and water runoff. Steeper slopes, especially those facing north and east, show closely spaced contour lines, indicating higher erosion potential. Conversely, wider contour intervals in flatter central areas suggest limited sediment load increase due to flow saturation. Identifying contour lines is essential for delineating catchment areas and understanding sediment dynamics within the watershed.

3.3 Watershed Delineation

The study used the Digital Elevation Model (DEM) to define the study area and identify the catchment area contributing to water flow at a specific point. A watershed, shaped by terrain, includes all land and water bodies, such as streams, reservoirs, wetlands, and groundwater, that drain to a common outlet. Larger watersheds contain smaller ones, depending on the location of the outflow point. Watersheds are vital because activities within them, whether natural or human-induced, directly impact water flow and quality at the river's exit point.

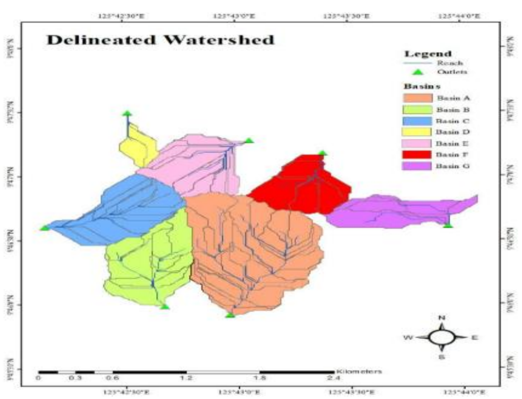

Fig. 4 Delineated watershed of the study area.

Figure 4 illustrates the delineated watersheds of Hinatuan Island, which collectively span a total area of approximately 1,275 hectares. The geographical attributes of the study area present 7 distinct watersheds, which were chosen for delineation. Each basin possesses a distinct primary outlet, necessitating separate analysis by the SWAT model to ensure precise delineation. The selection of these 7 stream basins was also influenced by the availability of discharge data gathered by the HMC.

After completing the delineation process, the project area was divided into separate sub-basins labeled A-G. Each sub-basin had a topographic profile detailing elevation metrics such as maximum, minimum, mean, and standard deviation, summarized in Table 2.

Table 2. Elevation and total area of different sub-basins.

Major Sub-basins	Minor Sub-basins	Total Area (ha)	Min Elevation (m)	Max Elevation (m)	Mean Elevation (m)
A	26	145.15	11	329	186.19
B	13	67.70	0	322	172.25
C	13	60.81	1	336	206.91
D	3	12.04	7	330	217.24
E	13	52.33	7	336	226.54
F	7	44.28	21	312	189.50
G	5	40.08	0	288	149.37

Furthermore, the output included important features like river streams, longest paths, and outlets. The analysis showed that Basin A has the largest area (145.15 ha) and the greatest number of sub-basins (26), while Basin D has the smallest area (12.04 ha) and fewer sub-basins (3). This result can be attributed to various factors including the topographic characteristics of the study area, the hydrological processes, and geological controls. It has been found out that larger subbasins may occur due to the flatter slopes and lower elevations, leading to a slower runoff and deposition processes compared to smaller subbasins with steeper slopes and higher elevation which likely to experience an increase in runoff and erosion rates leading to higher number of accumulated sediments [6].

3.4 Hydrological Response Units (HRUs) Results

Throughout the HRU process, each watershed within the study area was reclassified based on various land use, soil types, and slope characteristics. Regarding land cover, four classes were chosen and reclassified into different SWAT (Soil and Water Assessment Tool) codes using ArcSWAT software. As an illustration, "FRST" represents Forest Mixed, "BARR" for Barren, "WATR" for Water, and "URBAN" for Residential areas. Similarly, soil classes were reclassified, with codes like "Ws15-1-2b-6108" representing Sandy Clay Loam based on the updated HSWD user soil database.

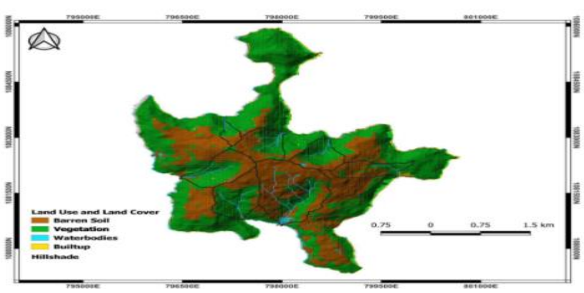

Fig. 5 Land use reclassification in the watershed.

Figure 5 visually depicts a specific land use class within the watershed. The study employed a land use land cover map to identify and categorize various types of land cover in the watershed. This map was created using satellite imagery and a supervised Support Vector Machine (SVM) classifier. Four distinct land use classes were identified and mapped in this area. Table 3 provides a summary of the total land use for each sub-basin.

Table 3. Different land cover classes and its sub-basin area.

	Land Cover Classes	SWAT Classes	Sub-Basin Area (ha) A	B	C	D	E	F	G	Total (ha)
Land Use	Forest-Mixed	FRST	102.33	44.85	36.01	6.66	28.12	29.85	15.42	263.24
	Barren	BARR	39.72	22.48	24.36	5.21	24.09	13.85	24.58	154.29
	Water	WATR	3.07	0.09	0.21	0.17	0.07	0.56	0.06	4.23
	Residential	URBN	0.03	0.28	0.23	-	0.05	0.02	0.02	0.63
Soil	Sandy Clay Loam	Ws15-1-2b-6108	145.15	67.7	60.81	12.04	52.33	44.28	40.08	422.39

The watershed's land cover is predominantly a Mixed Forest Area, covering 263.24 hectares and accounting for 63.32% of the total. Barren land makes up the next largest portion at 154.29 hectares (36.53%). Water bodies are minimal, occupying 4.23 hectares (1%), while Residential areas are the smallest category at just 0.63 hectares (0.15%). This dominance of mixed forest types suggests a significant influence on the local ecosystem, including providing wildlife habitat, regulating climate, and preventing soil erosion.

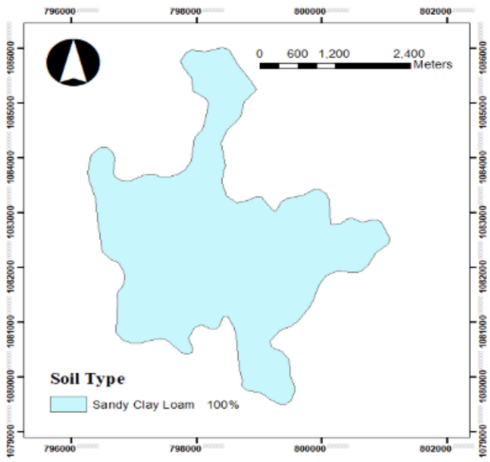

Fig. 6 Reclassified soil map.

Figure 6 presents the distribution of soil types across the mountainous watershed area, highlighting clay loam as the predominant soil type. In Surigao del Norte, the soil composition varies, with the mainland primarily consisting of Anao-aon/Malimono clay loam (60%), Kabatohan sandy clay loam (20%), and Malalag clay loam (20%) known for moderate drainage and good permeability, making them suitable for agriculture (Provincial Government Office of Surigao del Norte). In the northern region, including the study area, Kabatohan or sandy clay loam is dominant. This soil type, with a balanced mix of sand, silt, and clay, provides better drainage and moderate water retention compared to traditional clay loam.

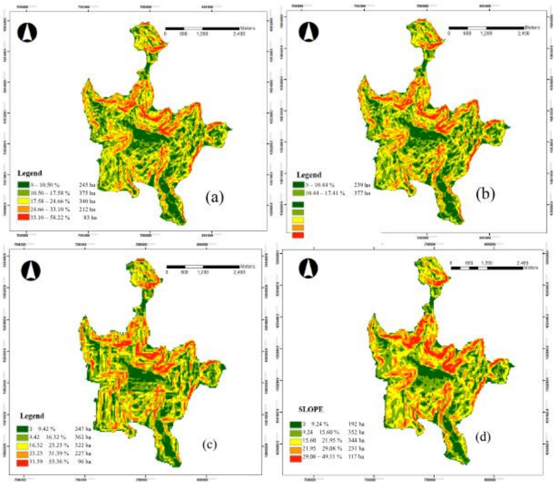

Fig. 7 Reclassified slope map for (a) 2007, (b) 2008, (c) 2015, and (d) 2021.

Figure 7 shows the different slope classes and their respective catchment areas for the years 2007, 2008, 2015, and 2021. These data are categorized into five distinct percentages, obtained through DEM analysis used for delineating boundaries and river networks, resulting in a slope classification map.

The study area's slope distribution underwent significant changes from 2007 to 2021, primarily influenced by mining activities. In 2007, nearly flat areas (0-10.50%) constituted about 20%, with the largest portion (375 hectares) having moderate slopes (10.50-17.58%). Steeper slopes (17.58-24.66%) accounted for 27%, while very steep slopes (24.66-33.10%) covered 212 hectares (17%). The steepest areas (33.10-58.22%) were 83 hectares.

By 2015, flatter areas (0–9.42%) still made up 20% of the land, with some slopes reaching up to 53.36%. By 2021, a notable shift occurred: flat areas (under 9.24%) decreased, while steeper slopes (up to 29.08%) increased, with the steepest zones expanding to 117 hectares, rendering them unsuitable for development due to high risks of erosion and landslides. These changes in slope configuration are primarily attributed to mining operations, which alter surface topography and affect slope stability [7]. Slope is a critical factor in hydrological modeling as it directly influences runoff, erosion, and sediment transport. Steeper slopes enable greater sediment movement due to higher energy availability, which must be considered in sediment transport and yield estimations [8].

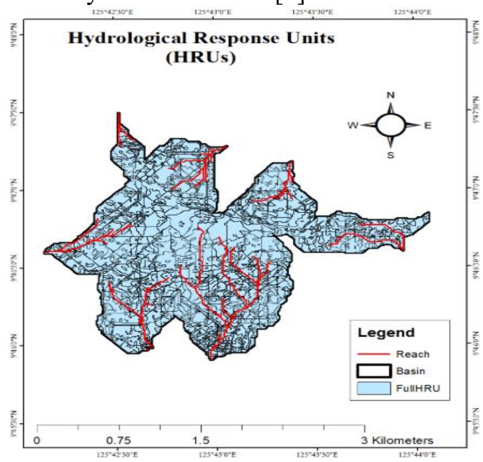

Fig. 8 The Hydrological Response Units (HRUs) result.

Figure 8 illustrates the HRU results, which integrate soil, land use/land cover (LULC), and slope data from the study area's DEM. The watershed is primarily covered by mixed forest (63.32%), growing on permeable and moderately draining sandy clay loam soils. Additionally, 83.33% of the watershed has gentle slopes, collectively influencing its hydrological processes.
From 2013 to 2021, notable changes in land use cover significantly influenced the watershed’s hydrological response. The HRU, which integrates land use, soil, and slope data, was key to analyzing these effects on water yield.

In 2013, mixed forest dominated about 63.32% of the area, underlain by sandy clay loam soils and mostly gentle slopes (83.33%), supporting moderate drainage and permeability. By 2015, shifts in land use—due to urbanization, agriculture, or natural disturbances—began affecting infiltration and runoff. These changes intensified by 2018, with possible forest fragmentation and land conversion altering water flow and storage.
By 2021, mixed forests had likely declined, replaced by other land uses, significantly impacting water yield through changes in runoff and groundwater recharge. The interaction among land cover, soil, and slope underscores the need for sustainable watershed management to mitigate these hydrological impacts.

3.5 Changes in Land Use Land Cover

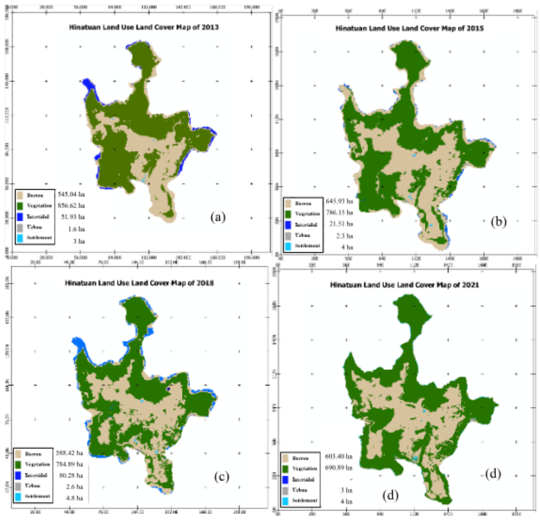

Fig. 9 Land Use Land Cover changes in (a) 2013, (b) 2015, (c) 2018, and (d) 2021.

Figure 9 (a–d) presents land use changes in the watershed from 2013 to 2021, using satellite imagery classified through a Support Vector Machine (SVM) method. Four land cover classes were identified: vegetation, bare soil, urban areas, and settlement ponds.
In 2013 (Fig. 9a), vegetation dominated the landscape (61%), while bare soil covered 39%. Urban areas and settlement ponds accounted for less than 1% combined. Despite mining activity, the area remained largely vegetated.
By 2015 (Fig. 9b), vegetation remained dominant, but bare soil increased by 58.36 hectares, linked to mining [9]. Urban areas and settlements also slightly expanded.
In 2018 (Fig. 9c), vegetation increased by 92 hectares, likely due to rehabilitation, while bare soil decreased. Urban areas slightly shrank, while settlement ponds grew by 0.8 hectares, aiding sediment control.
By 2021 (Fig. 9d), vegetation declined by 91 hectares, and bare soil expanded by 14.98 hectares. Urban areas grew modestly, while settlement ponds decreased by 0.8 hectares, indicating ongoing land use shifts driven by development and environmental interventions.

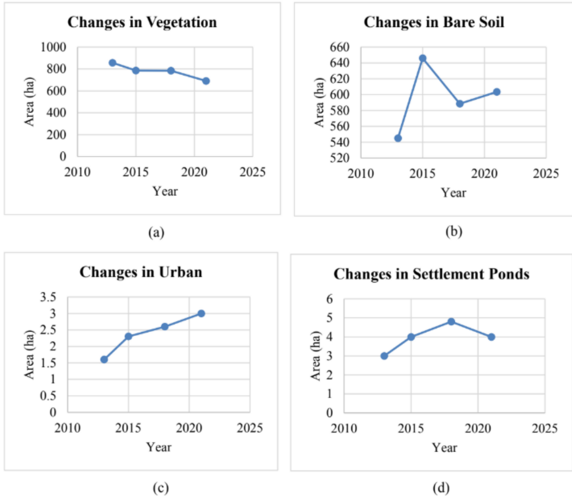

Fig 10. Land Cover changes in area (ha) across 2013, 2015, 2018, and 2021.

Figure 10 (a–d) illustrates changes in land use within the study area, highlighting the areas of bare soil, vegetation, urban zones, and settlement ponds over time.
In 2013, vegetation dominated, while bare soil covered a smaller portion. By 2015, bare soil expanded, and vegetation declined, indicating an inverse relationship. In 2018, vegetation increased due to rehabilitation efforts mandated by Section 71 of the Philippine Mining Act of 1995 [10] which requires mined areas to be restored for environmental safety.
Increased vegetation reduces sediment yield by stabilizing soil, enhancing infiltration, and trapping sediments [11, 12]. Meanwhile, settlement areas decreased in 2018 but generally increased in other years. Settlement ponds expanded until 2018 but declined in 2021, likely due to sediment buildup reducing their capacity, necessitating maintenance or dredging [9].

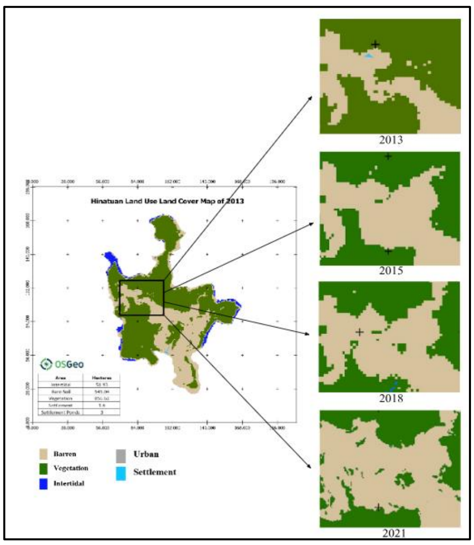

Fig 11. Observed Land Use Land Cover Changes in a specific area of Hinatuan.

The land use changes shown in Figure 11 highlight a clear shift in the landscape over time. In 2013, bare soil covered only a small area, but it steadily expanded in the following years, while vegetation decreased. This trend reflects the dynamic nature of land use and emphasizes the need for ongoing monitoring to support effective land management and conservation strategies.

3.6 SWAT Output Data

The SWAT simulation generates various output files, such as reach, subbasin, and HRU outputs, on daily, monthly, annual, or average yearly scales. These outputs provide summarized data for specific areas within the watershed and are essential for analyzing water resources. Key hydrological components include evapotranspiration (ET), water yield, surface runoff, percolation, lateral flow, return flow, and sediment yield. For this study, sediment yield from sub-basins 1 to 7. covering the Hinatuan Mining Corporation watershed, was analyzed from 2011 to 2021, reflecting the watershed's subdivision into sub-basins.

3.6.1 Simulated Sediment Yield

Figure 12 illustrates a consistent rise in simulated sediment yield (tons/ha/year) across four years. In 2011, sediment yield ranged from 11 to 127 tons/ha. By 2015, it increased to 13, 165 tons/ha, showing a significant rise. This upward trend continues in 2018, with the maximum yield increasing by an additional 6 tons compared to 2015. The sediment yield in 2021 experienced the most significant increase, jumping from 10–174 tons/ha in 2018 to 20–289 tons/ha, a rise of 115.744 tons/ha. This sharp escalation highlights severe sedimentation impacts, emphasizing the urgent need for effective erosion control. In terms of annual averages, 2021 recorded the highest mean sediment yield at 155.22 tons/ha, more than double the 69.43 tons/ha mean in 2013. Subbasins with steep slopes and closely spaced contour lines, particularly D, E, F, and G, exhibited the highest sediment accumulation. These areas, often barren and topographically unstable, are more susceptible to erosion, especially during rainfall events.

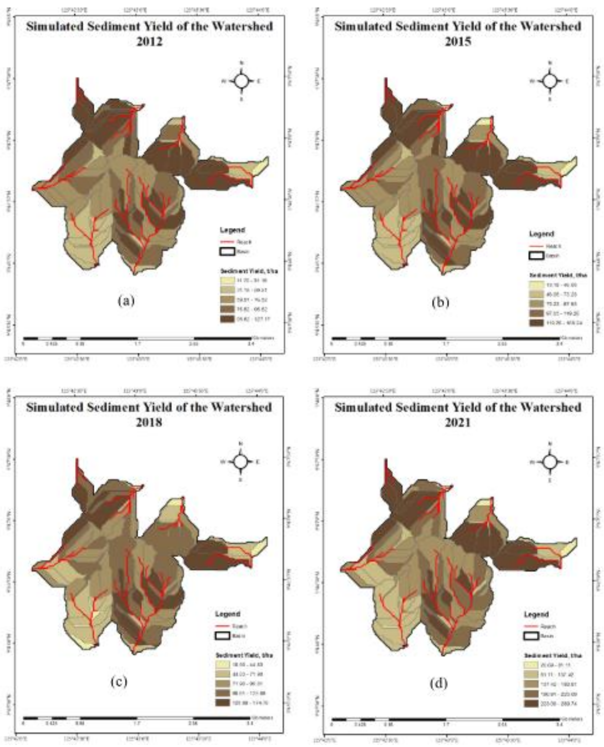

Fig 12. Simulated sediment yield in year (a) 2012, (b) 2015, (c) 2018, and (d) 2021.

Supporting studies such as those by Mishra et a. [13] and Semmahasak et al. [14] confirm that steep slopes significantly contribute to sediment yield due to gravitational erosion. Similarly, Maloles [15] demonstrated that mining activities increase sediment output, while Martín-Moreno et al. [16] highlighted the importance of erosion control in mitigating such effects. Natural events like typhoons further exacerbate sedimentation. These high-intensity storms, common in tropical regions, bring heavy rain and strong winds, triggering severe erosion, especially on vulnerable terrains [17, 18]. Therefore, both human and natural factors play critical roles in sediment yield increases, reinforcing the need for targeted watershed management strategies.

Table 4. Mean annual sediment yield values for 2012, 2015, 2018, and 2021.

Year	Mean Sediment Yield (t/ha)
2012	69.44
2015	89.21
2018	92.63
2021	155.22

Table 4 shows a clear increase in mean sediment yield over time: from 69.44 tons/ha in 2012 to 89.21 tons/ha in 2015, then 92.63 tons/ha in 2018, with the highest jump to 155.22 tons/ha in 2021. This rise suggests changes in watershed dynamics, land use, or climate factors like tropical cyclones. Key contributors may include intensified mining, altered precipitation patterns, land cover changes, or shifts in watershed management [19].

3.6.2 Sediment Yield and Precipitation

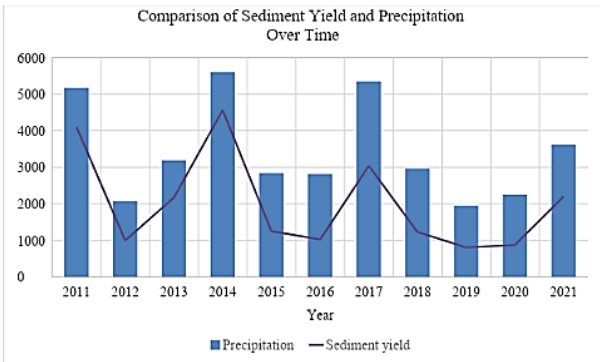

Fig 13. The relationship between sediment yield and precipitation.

Figure 13 illustrates the 10-year relationship between precipitation and sediment yield, highlighting how precipitation influences sediment transport and deposition. In 2014, both precipitation and sediment yield peaked, while 2019 recorded the lowest values for both. Precipitation is a key driver of erosion and sediment transport, with sediment discharge closely linked to rainstorm intensity and frequency [20]. Fluctuations in sediment yield over time correspond to changes in precipitation as well as land use alterations, such as mining expansion, which impact sediment dynamics [21]. Overall, sediment yield shows a direct proportionality to precipitation, consistent with findings by Langbein [22].

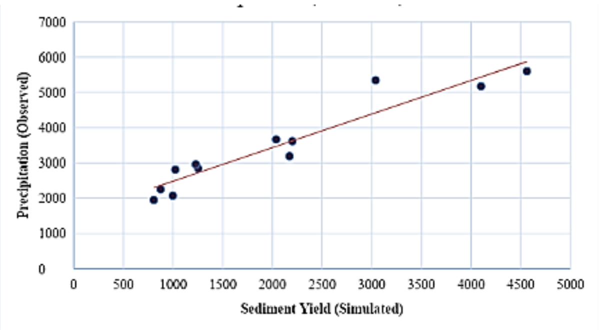

Fig 14. The relationship of sediment yield and precipitation.

Table 5. Coefficient of determination (R^2) interpretation Source: Man et al. [21].

Coefficient Determination (R^2) Values	Interpretation
> 0.91	Very good model prediction
0.81-0.90	Fairly precise model prediction
0.66-0.80	Model prediction can only distinguish low-mid-high values
0.50-0.65	More than 50% of Y variance is affected by X variance

Figure 14 and Table 5 show a coefficient of determination (R^2) of 0.9068 between observed precipitation and simulated sediment yield. This value, within the 0.81–0.9 range, indicates a fairly precise model prediction based on Table 7 criteria. R^2 measures how well the independent variable (precipitation) explains the variance in the dependent variable (sediment yield) [23]. Therefore, the figure suggests a strong, reliable relationship between observed and simulated data, confirming the model's accuracy [24].

4. CONCLUSION

This study demonstrated the effectiveness of integrating ArcGIS and SWAT models to simulate sediment yield in a watershed. These tools supported key processes such as DEM processing, watershed delineation, land use and soil reclassification, slope analysis, HRU generation, and sediment yield simulation using historical data.

Mean sediment yield showed a consistent increase over time: from 69.44 t/ha in 2012 to 89.21 t/ha in 2015, 92.63 t/ha in 2018, and a sharp rise to 155.22 t/ha in 2021. The significant jump in 2021 is linked to Super Typhoon Odette, whose intense winds, combined with steep slopes and erodible soils, caused elevated erosion rates. Overall, sediment yield increases are attributed to land use changes, terrain features, and climate-driven erosion.

Precipitation was a key factor influencing sediment accumulation, with a strong correlation between observed rainfall and simulated sediment yield (R^2 = 0.9068), indicating reliable model predictions.

The GIS-SWAT integration provides valuable visual tools like maps and charts, improving understanding and communication of sediment dynamics. This supports stakeholders and agencies in making informed decisions on soil and water conservation and optimizing settling pond placement to reduce sediment risks in critical areas.

5. RECOMMENDATION

The SWAT hydrological model is a valuable tool for watershed hydrological modeling, but it requires complete and reliable meteorological and hydrological data for proper calibration and validation. Future research should focus on improving calibration and validation methods, especially in data-scarce areas, to enhance model accuracy and performance. Successful calibration depends on strong agreement between simulated and observed data, which primarily requires daily precipitation and discharge records, global data alone is insufficient. Therefore, continuous local data collection and processing are essential. Additionally, exploring simpler, user-friendly alternative models that still deliver reliable results is recommended for future studies.

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