Sriwijaya Journal of Environment
Article
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Predicting Soil Erosion Using the Soil and Water Assessment Tool (SWAT) Model in Giritengah Catchment Area

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Article history

Received	Received in revised form	Accepted	Available online
09 February 2023	29 March 2023	02 April 2023	13 April 2023

Abstract. Giritengah catchment is 5 km to the southwest of Borobudur Temple and is an area that has been designated as a buffer zone that acts as a support zone for tourism activities in the Borobudur Area. The purpose of this study is to predict erosion in the Giritengah catchment and develop a scenario for the application of the right Soil and Water Conservation (SWC) techniques to reduce erosion in the Giritengah catchment. Erosion estimation is carried out using the Soil and Water Assessment Tool (SWAT) model. The results showed that the average amount of erosion is 30.7 tons/ha/year with the highest average erosion being on dry land use. The classification of predominant Erosion Hazard Levels is in the very low, low, and heavy classes. The application of the suitable SWC technique in the form of bench and ridge terrace's structure is expected to be able to reduce erosion that occurs in the Giritengah catchment to very low Erosion Hazard Level (EHL) classes reaching 60.4% of the total area and eliminate heavy EHL classes.
Keywords: soil, SWAT, water, erosion, hazard

1. Introduction

Watershed is a land area that is topographically limited by mountain ridges that accommodate and store rainwater to then channel it to the sea through the main river [1]. In addition to hydrological functions, watersheds also have a role in maintaining biodiversity, economic value, culture, providing productive land, and can be used for human interests.

Humans as an active component of environmental managers will determine the patterns and patterns of land use found in a watershed area. This can increase the pressure that occurs in the watershed due to changes in land use that occur [2]. The impact that occurs from the increase in land use change is the increase in critical land, sedimentation, and increased soil erosion.

Soil erosion in watershed ecosystems generally occurs due to land use that does not comply with soil and water conservation principles. These land use activities usually occur in areas that have the potential which can be developed for the sake of improving the community's economy, such as agriculture, residential development, and tourism. The tourism strategic area is an example of an area experiencing land use change with a fairly high number due to the development of commercial land [3]. One of the areas that are a strategic tourism area is the Borobudur area, Magelang Regency.

The Borobudur area has significant potential and is included in the National Tourism Strategic Area (KSPN). This makes the Borobudur Temple area a center for the growth of new settlements for the surrounding area in the form of hotel development, agriculture, and village tourism development activities. Villages that have become tourist destinations include Candirejo Village, Tanjungsari Village, Karanganyar Village, and Giritengah Village [4]. One of the areas indicated for land use change is the Giritengah Catchment Area (CA) which is a sub-sub-watershed of Tangsi, Progo watershed.

Geographically, Giritengah Village is located in a hilly area, namely the slopes of the Menoreh hills, and included in zone 5, namely as a supporting area for tourism activities (buffer zone) in the Borobudur Area [4]. This research aims to analyze the amount of erosion rate and the level of erosion hazard in Giritengah CA and to develop a design for soil and water conservation techniques that are suitable to be applied in the study area.

2. Material and Methods

2.1. Research sites

This research was conducted at Giritengah CA, Borobudur District, Magelang Regency, Central Java. The study area is located at coordinates 7° 37'22.6" - 7° 38'48" South Latitude and 110° 10'28.4" - 110° 11'35.6" East Longitude. This research was conducted from December 2021 to April 2022.

2.2. Tools and materials

The tools used in this study consisted of a laptop, Ms. Office, ArcGIS 10.4, Arc SWAT 10.4, SPAW Hydrology, GPS, camera, stationery and tally sheet, label, shovel, sample ring, hammer, and plastic. The material used in this study consisted of two data, primary data, and secondary data. Primary data is in the form of soil samples related to the physical and chemical properties of the soil at Giritengah CA. Secondary data consists of the Digital Elevation Model (DEM), river network maps, land use maps, soil type maps, and climate data in the form of daily rainfall data, daily maximum and minimum temperatures, daily humidity, wind speed, and daily solar radiation.

2.3. Methods

This research consists of several stages starting from data collection, data input process, running the model, and doing scenarios for the application of Soil and Water Conservation (SWC) techniques.

Data retrieval

The data used in this study consisted of two types of data, namely primary data and secondary data. Primary data in the form of soil samples related to the physical and chemical properties of the soil were taken by using disturbed and undisturbed soil samples. The secondary data obtained from several agencies and websites include rainfall data, climatic data, river network maps, land use maps, soil maps, and location maps. Estimation of erosion using the SWAT method requires several related applications, namely the 2012 version of SWAT and ArcGIS 10.4. In addition, there are several main processes in entering data in the SWAT model, namely entering climate data, processing data, and creating a soil database. Making a soil database by inputting soil analysis data in the user soil table on Ms. Access. Soil data resulting from the laboratory analysis is inputted using the SPAW Hydrology software. In this research, data calibration regarding the result was not processed since the discharge data was very limited.

The SWAT model simulation is carried out using several stages ranging from watershed delineation based on DEM data input, formation of HRU based on soil type map input, land use maps, and slope class maps that are read from DEM, generating climate data with the Weather Data Definition feature, and model simulation. The simulation is carried out after the user enters the determination of the simulation output in the form of daily, monthly, or yearly as well as what data he wants to print.

The erosion simulation results can be grouped based on the classification of the erosion hazard level (EHL) classification is determined by comparing the erosion results obtained and the effective soil depth on land into the EHL class (based on the Regulation of the Minister of Forestry Number P32/Menhut-II/2009).

The scenario applied in the analysis of the Soil and Water Conservation (SWC) technique is by using a manual calibration tool on the SWAT software by entering a value in P which is the soil and water conservation factor [5]. The form of the SWC technique that is applied to the scenario carried out is bench and ridge terraces.

3. Results and Discussion

3.1. Hydrological Analysis

The delineation of the Giritengah CA by the SWAT model results in information on micro watershed boundaries, river network maps, and sub-basin maps. The outlet points are found at coordinates 7° 37'22.2" South Latitude and 110° 11'01.7" East Longitude and 32 sub-basins are formed with an area of 334.8 ha.

Hydrological Response Unit (HRU) is a hydrological analysis unit that is formed based on land use, slope class, and soil type. It results in 238 HRUs and 32 sub-basins (Figure 1). The large variety of HRUs formed since the Giritengah CA has varied land uses dominated by the dry land field with a total area of 194.1 ha which is spread almost throughout the catchment area, from upstream to downstream at flat to very steep slope classes.

The SWAT model requires climate data for the last 5 (five) years, namely from 2017 to 2021. The Running model is carried out using data that has been prepared previously, namely micro watershed delineation data, as well as climate data. The climate data used are daily rainfall data, daily maximum and minimum air temperature, wind speed and daily solar radiation, and daily relative humidity. In the process of running the model, there is a warming up for 2 years, which means that the first 2 years (2017-2018) are used for warming up the model. The process of warming up the model is used to stabilize the base flow conditions in the simulation until equilibrium conditions in the hydrological process are formed [6].

In an ecosystem, the availability of water has an important role. The concept of the environmental hydrologic cycle states that the amount of water in a certain area on the earth's surface is influenced by the amount of water entering or absorbed (input) and water leaving (output) over a period of time [7]. [8] Also said that the water balance is the relationship between the total incoming water and the lost water. Incoming water can be in the form of precipitation and condensation, then the water loss is in the form of base flow, runoff, percolation, intermediate flow, lateral flow, and evapotranspiration.

The average precipitation at Giritengah CA is 2271 mm/yr. The surface flow formed is 1230.78 mm, then the lateral flow is 105.48 mm, the backflow is 610.97 mm, the percolation is 658.38 mm, the vapor from the shallow aquifer is 9.42 mm and the evapotranspiration is 269 mm.

The hydrological analysis shows that the total surface runoff is 1230.78 mm, greater than the lateral flow which has a value of 105.48 mm. This is in accordance with research conducted by [9] that the large surface runoff generated results in low lateral flow. This high runoff is caused by the natural physical condition of Giritengah CA. The study area has a total slope area with classifications IV and V of 27.6 and 48.5% of the total area and in terms of land use, it has an area of the dry land field and settlement with a total area of 58 and 16.2% of the total area. The slope of 25-40% (hilly) and the use of dry land in the form of dryland agriculture and settlements are the dominant factors for the amount of runoff. The slope also affects the runoff, where the large runoff is in line with the magnitude of the slope [9].

In addition to surface flow, the evapotranspiration in Giritengah CA is 269 mm. Factors that affect evapotranspiration include temperature, wind speed, water vapor pressure, and relative humidity [10]. The average annual maximum and minimum temperatures from 2017-2021 are 27.2 °C and 20.3 °C with the highest average maximum temperature occurring in October, which is 29.3 °C. The humidity factor also affects the amount of evapotranspiration. The average air humidity in 2017-2021 is 87% with the lowest average humidity occurring in September, which is 80.2% and the highest in May with up to 90%. This is in line with [11] that the greater the humidity in the surrounding air, the smaller the evapotranspiration.

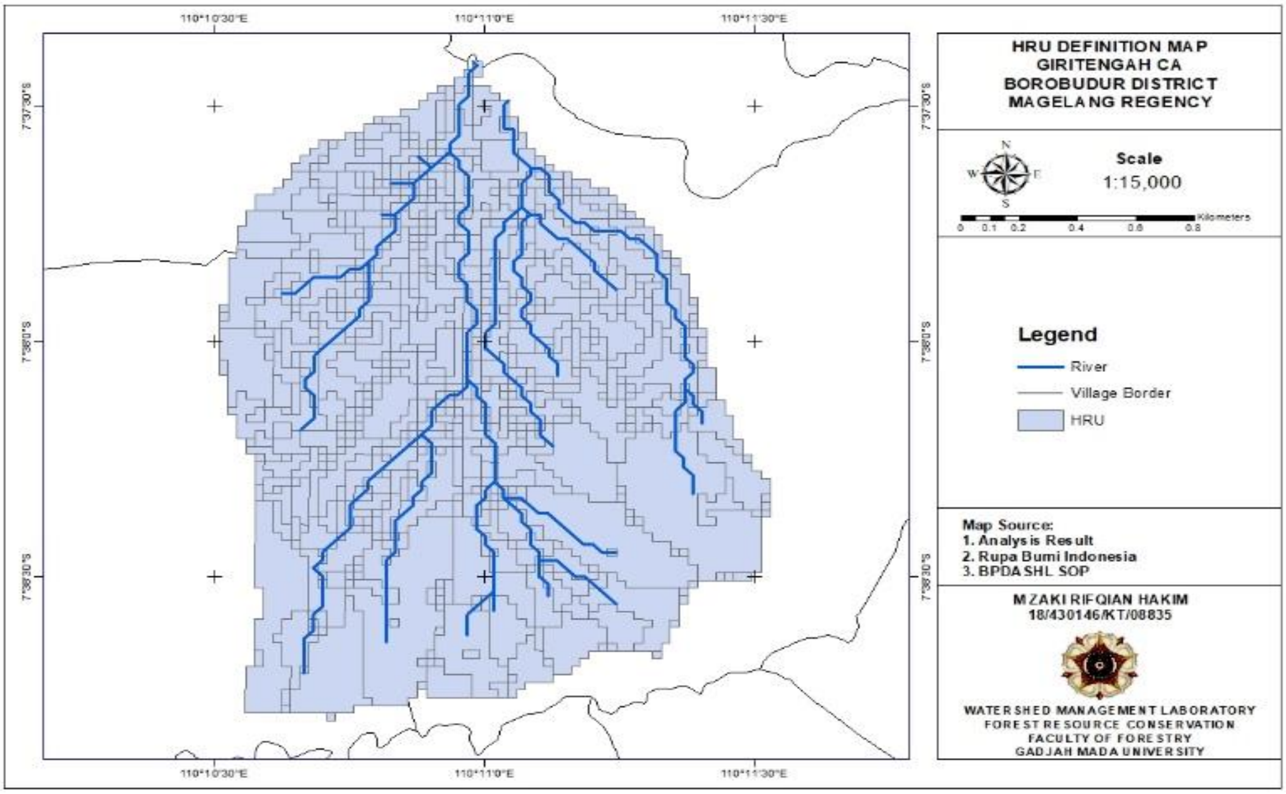

Figure 1. Map of HRU

3.2. Erosion Prediction Analysis

According to [12], soil erosion is a complex process and depends on the nature of the soil, vegetation, and the intensity of rainfall that occurs. Erosion occurs as a result of the transportation of soil or parts of land from a place by water or wind [13] In addition to this, land use also accelerates soil erosion due to decreased soil fertility caused by land tillage carried out [12].

Erosion simulation in the SWAT model is carried out for each HRU (Figure 1). The severity of erosion in each HRU is influenced by land use, constituent vegetation, and land slope. The erosion rate resulting by the SWAT simulation starts from the smallest rate of 0.7 tons/ha/year to the largest 195.4 tons/ha/year with an average erosion rate of 30.7 tons/ha/year. The diagram below shows the average amount of erosion at each land use.

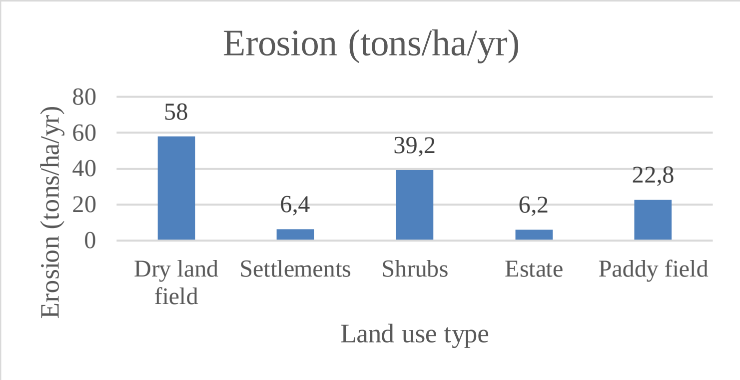

Fig 2. Erosion of each land use

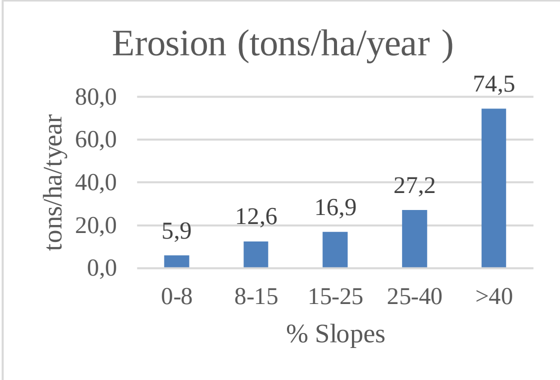

Fig. 3. Erosion of each slope class

Based on the above graph and Figure 2, the dry land field has the largest erosion rate compared to other land uses, followed by shrubs, paddy fields, settlements, and then estates. The dry land field, shrubs, and paddy fields is the biggest contributor to the erosion process. According to [14] land use significantly affects the hydrological output of a watershed. This statement is also reinforced by [15] showed that in the SWAT simulation, land use affects the loss of soil material on land. This proves that on dry land and paddy fields, it affects the occurrence of erosion due to the use of the land there is land cultivation by the community which causes the soil aggregate to become unstable and easy to erode. In addition, the shrubs also have a high erosion value sinces the dominant shrubs are in the slope class V, thus affecting the velocity of the soil surface flow that can transport particles in the soil.

The dry land is dominated by vegetation such as corn, cassava, and chili. The erosion rate at the dry land field is 58 tons/ha/year. This is because agricultural crops are plants that require soil management in each growing season which causes the soil to be easily eroded. In addition, vegetation on agricultural crops has a small canopy so that plants are less able to protect the soil surface from the amount of energy produced by falling rainwater which can destroy soil aggregates thereby increasing the occurrence of erosion [16] . The dry land fields spread over each slope class and the dominant slope is in the V slope class (>40%). As much as 65.3% of the dry land field locations are in the slope class V, then 23.9% are in slope class IV thus this affects the runoff that occurs in the use of dry land. This is certainly in line with the statement of [9] that the slope affects the runoff, where the large runoff is in line with the magnitude of the slope. As the slope of the slope increases, the intensity of erosion will be higher [17].

The biggest contribution after the dry land field to erosion was found in the use of shrubs or bush land. The amount of erosion caused by land use in the form of shrubs is 39.2 tons/ha/year. Shrubs are scattered upstream of the Giritengah CA, have a total area of 16.2 ha, and are only in grades IV and V, which are classified as very steep slopes. As much as 97.7% of the total area of shrubs land is located on slope class V (>40%), followed by slope class IV with a percentage of 2.3%. With the large slope of the scrub land and the absence of land use by the community, the erosion that occurs is large. Agricultural land is always cultivated by farmers so that it tends to be preserved compared to shrubs which are neglected areas and not maintained.

Other land uses are paddy fields which have an area of 11.3% of the total area of the watershed, spread on slopes I to IV and most of them are downstream of the watershed. The dominant use of paddy fields is in slope classes II and III with a percentage of 43.7% and 31.3% of the total area of rice fields. Land use in the form of rice fields has an erosion contribution of 22.8 tons/ha/year. This is influenced by the opening of rice fields so that the kinetic energy produced by rainwater falls directly to destroy soil aggregates. In addition to this, agricultural crops are plants that require soil tillage in each growing season. This continuous land tillage causes the soil to be easily eroded. The vegetation planted by the community in the rice field area includes corn, cassava, and grass with an irrigation system in the form of rain-fed rice fields.

Land use in the form of settlements has an area of 54.2 ha and is a settlement with a medium density. Settlements are the second largest land use after dry land fields with a percentage of 16.2% of the total watershed area. Settlements contribute to erosion by 6.4 tons/ha/year. Then the last land use is estate land with a total area of 32.5 ha and is located in the middle to downstream of Giritengah CA. Plantation land is dominated by clove and caliandra plants.

Other factors that influence erosion are the slope and soil type. The erosion analysis in each slope class show results that are in accordance with the theory presented by [17] that the greater the slope, the higher the intensity of the soil for water erosion. Slope class V (>40%) has the highest erosion rate compared to other slope classes with a size of 74.5 tons/ha/year, followed by slope classes IV, III, II, and I with an erosion average of 27.2 tons/ha/year, 16.9 tons/year. ha/year, 12.6 tons/ha/year, and 5.9 tons/ha/year. This is also related to the kinetic energy resulting from the large runoff flow in line with the increasing slope of the slope. Figure 5.9 shows that the average value of erosion increases with the steeper slope class.

Soil type is also a factor that affects the amount of erosion. Each type of soil has a different level of sensitivity to erosion. Soil sensitivity is whether or not the soil is easily eroded. The value of erosion will be greater with the greater the value of the sensitivity and erodibility of the soil. Soil that has coarse grains, the soil will be easily separated or split by raindrops, but soil that has coarse grains can be more resistant to the carrying capacity of surface runoff.

Giritengah CA has one type of soil, namely Latosoll which has a code (I-Ao-2/3c). Latosol soil is soil that has parent material derived from volcanic rock resulting from volcanic eruptions and is formed from the weathering process of igneous and sedimentary rocks. Soil texture serves as a determinant of water management in the soil and affects penetration, infiltration speed, and the ability to bind water to the soil. According to [18], soil that tends to be clayey has a better water-holding capacity than soil with a texture of sand and dust so that it is less susceptible to erosion. This is related to [18] research that erosion event is influenced by the amount of water that seeps into the soil as a result of rainwater infiltration which causes soil weight to increase. Latosol soils are generally very poor in nutrients [19]. In general, Latosol soil is very common can be found in mountains at all climatic zones.

The Giritengah CA has a solumn depth of 60 cm to more than 100 cm and is included in the deep soil depth. The results of EHL classification can be seen in Figure 4 below.

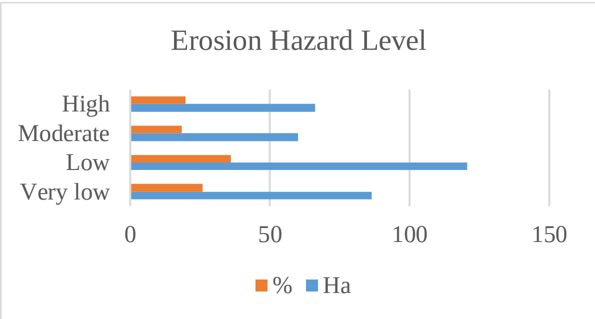

Fig. 4. Erosion Hazard Level

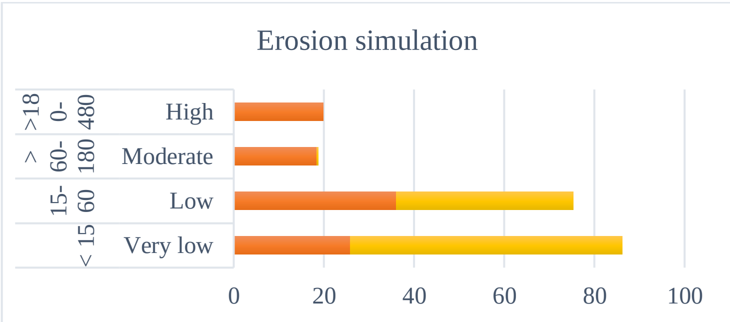

Fig. 5. Erosion simulation

The most significant erosion occurred in the HRU of dry land which is in the slope class V. Then, the medium EHL classification is spread over the upstream, middle, and downstream areas of the Giritengah CA. Medium EHL is significantly located in the dry areas upstream of the Giritengah CA with slope class V (>40%). [14] states that the characteristics of the watershed that affect the amount of erosion value are topography and the area of the catchment area.

3.4. SWC Application Scenarios

Soil and water conservation in general is defined as a way of utilizing each plot of land in a way that is in accordance with the capabilities possessed by the land and treating it according to the necessary conditions so that there is no damage to the soil [20]. Damage to soil caused by a lack of management of soil sustainability can cause erosion. Therefore, the SWC structure is needed to minimize the occurrence of surface runoff which can increase the rate of erosion.

The bench terrace was chosen because the terrace is effectively able to withstand an erosion rate of up to 79.21% [21]. The application of the terrace refers to land use data and slopes. Judging from the use of land in the form of fields, paddy fields, and estates with contours that vary from gentle to steep, terrace structure is appropriate to practice. Terrace structure is also a soil conservation technique that has a fairly high level of application by the community and is a conservation building that is relatively not easily damaged and facilitates soil management practices [22]. Then the ridge terrace was chosen because the application of the SWC technique is suitable for a slope of 10-40%, the cost is relatively cheap, and the level of reduction in the area of cultivation for the application of this technology is relatively low [22]. The bench terrace scenario is applied to the dry fields, rice fields, and plantations in slope classes III, IV, and V while the scenario using ridge terraces is applied to dry fields, rice fields, and plantations in slope class II (8-15%). According to [23] the P value for soil conservation techniques in the form of bench terraces is 0.15, and the ridge terrace is 0.01.

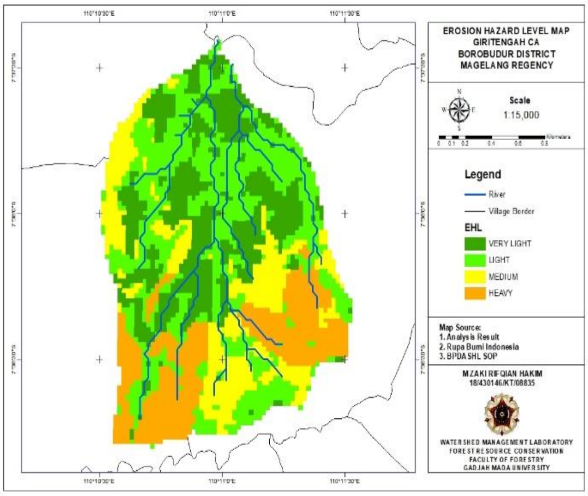

Fig. 6. The Erosion Hazard Level

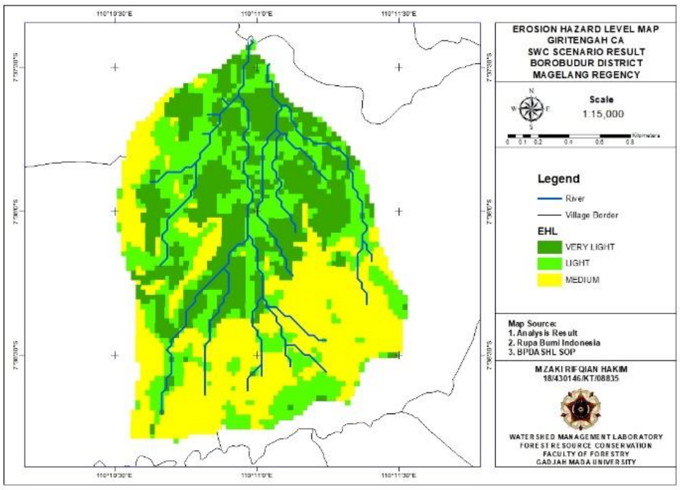

Fig. 7. EHL after SWC Simulation

The results of the applied scenario show that the application of the SWC technique in the form of bench terraces and ridge terrace is able to reduce the average amount of erosion that occurs in Giritengah CA. The simulation results that EHL in the heavy and medium classes changed quite significantly with the percentage of the area before the scenario of 19.8% to 0% of the total area of the heavy class and 18.4% to 0.4% of the total area in the medium class. The simulation of the SWC technique changes into very light and light EHL. The criteria for very light EHL changed from a percentage of only 25.8% to 60.4% of the total area, and light EHL increased by 3.3% of the total area to 39.3%. This indicates that the bench and ridges terraces are significantly able to reduce erosion. Meanwhile, the HRU distribution map experienced changes in EHL after the SWC scenario (Figure 7).

4. Conclusion

The conclusions of the SWAT model analysis in this study are:

a. The average erosion in Giritengah CA is 30.7 tons/ha/year and the highest average erosion at the dry land field with the average erosion rate in dry fields, settlements, shrubs, estate, and paddy fields of 58 tons/ha/year, 6.4 tons/ha/year, 39.2 tons/ha/year, 6.2 tons/ha/year, and 22.8 tons/ha/year. The highest Erosion Hazard Levels (EHL) occurred at the dry land fields with the slope class V.
b. The design of appropriate soil and water conservation techniques is applied to the Giritengah CA in the form of bench and ridge terraces. The terraces were able to reduce the erosion rate up to a very low EHL class of 60.4% and eliminate the heavy EHL class.

Acknowledgement

Thank you very much to the RTA Program of UGM of the support to our research at the scheme of Final Project Recognition, year 2022.

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