Soil Erosion Prediction and Risk.

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Soil erosion prediction and risk assessment using RUSLE model and GIS techniques in the Nangka watershed

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Abstract: Soil erosion in the Nangka watershed has always been a matter of concern. Over the last decade, soil erosion has led to continuous environmental problems. A thorough examination of the extent of the problem was required to identify an appropriate soil conservation strategy within the watershed. This study was conducted to observe erosion rates and map out the erosion hazard level. Erosion predictions were analysed by using the Revised Universal Soil Loss Equation (RUSLE) model with the help of ArcGIS software. RUSLE was selected because of its quantitative ability to estimate average annual soil erosion and its compatibility with the GIS interface. The potential hazard of soil erosion was classified and ranked into five class categories as set by the national authority. The results reveal that the Nangka watershed is prone to soil erosion with the annual average values ranging from 1.33 $Mg \cdot ha^{-1} \cdot y^{-1}$ to 2472.29 $Mg \cdot ha^{-1} \cdot y^{-1}$. High soil erosion rates of 9.8% are in severe (class IV) and very severe (class V) conditions, primarily in the upper course of the watershed. The low annual average of soil erosion (class I and class II), which accounted for 75.95% of the total erosion, mostly took place in the steepness below 35%. The remaining area of 14.25% within the watershed is in moderate condition (class III). It is expected that the results of this study will help the authority in the implementation of soil conservation measures.

Keywords: conservation measures, erosion hazard level, GIS techniques, RUSLE, soil erosion, watershed

INTRODUCTION

Soil erosion has become an important issue on the agenda of provincial and national authorities in Indonesia. This issue leads to loss of water-storage capacity of the watershed and surface water pollution. As those are applied in many countries, there are many approaches for soil erosion assessment. Pandey *et al.* [2021] recorded and reviewed a total of 14 methods including 4 methods that provide quantitative estimation while the other 10 methods are used for qualitative assessment of soil erosion vulnerability. Field measurements used to be a popular choice, but now the empirical model has been widely used because it requires a short time for analysis and low costs. Detailed field measurements are time-consuming and expensive, and for broad area erosion risk assessment, data acquisition at low cost is the primary issue [Ai *et al.* 2013]. With the rapid development of geospatial technology and information, the growth of geographic information system (GIS) has been expanded where land use data are more spatially described with levels of spatial resolution [Rizeei *et al.* 2016].

Soil erosion assessment is often difficult because of the complicated interaction of numerous parameters, including land use diversity, climate, human activities, and topography. Soil erodibility is affected by soil texture, soil structure, soil permeability, and soil organic content. According to Arsyad [1989], the size of the erosion is strongly influenced by several natural factors, such as slope, the state of vegetation, and the volume of water as erosion power. The steeper the state of the slope, the greater the erosion, and the more plants or vegetation, the less erosion will occur. It is also recognised that the greater the volume of water, the stronger the erosion power.

Since the introduction of the universal soil loss equation (USLE) by WISCHMEIER and SMITH [1978] and the revised universal soil loss equation (RUSLE) by RENARD *et al.* [1991] and MCCOOL *et al.* [1995], the phenomena of soil erosion has been studied extensively both experimentally and numerically [ABDO, SALLOUM 2017; AI *et al.* 2013; AZADBAKHT *et al.* 2019; FARHAN, NAWASEH 2015; GUO *et al.* 2020; LANORTE *et al.* 2019; LEE *et al.* 2017; MALLICK *et al.* 2014; PROFFIT 1983; QIWEI *et al.* 2020; RIZEEI *et al.* 2016; SAADI *et al.* 2010; SCHMIDT *et al.* 2019; SHARMA 2010; SRINIVASAN *et al.* 2021; VIJITH, DODGE-WAN 2020; ZHANG *et al.* 2003]. These studies were carried out in various regional conditions ranging from mountainous areas to lowlands. SCHMIDT *et al.* [2019] quantified the monthly rates of soil loss in Switzerland with the altitude ranging from 192 to 4633 m a.s.l. QIWEI *et al.* [2020] evaluate the potential danger of soil erosion in the typical karst area in China with an average altitude above 1000 m, whereas ABDO and SALLOUM [2017] calculated the annual rate of soil erosion and its spatial distribution in the Syrian coastal basin system. USLE or RUSLE, under the support of GIS technology and high-resolution remote sensing image, were widely adopted and employed to interpret the intensity of soil erosion and soil loss tolerance, including the natural disaster situation such as flood season [LI, WEI 2014] and post-natural disaster situation such as post wildfires [LANORTE *et al.* 2019].

Based on the erosion rate, the level of erosion hazard can be identified and a grading map can be generated. The level of erosion hazard is the level of a possible threat of damage caused by erosion on a watershed. The level of erosion hazard is obtained by comparing the level of erosion in a land unit with an effective depth. The shallower the solum of the soil, the less soil that can be eroded. This erosion hazard classification can provide an overview of the extent of the hazard in the watershed so that it can be used as a guide in watershed management.

The objectives of this study were to quantify the soil erosion rate and to delineate the spatial and temporal patterns of soil erosion hazards within the Nangka watershed. The prediction of soil loss will guide and allow decision makers in managing the environmental planning within the area and nearby basin. With the development of technology, a spatial database processing system is needed to accelerate and make it easier to detect locations while providing an overview of locations and study results in the form of a JPEG file for the basis of decision making by the authority. In order to meet the objectives, a geographic information system using ArcGIS desktop software has been employed.

MATERIALS AND METHODS

AREA OF STUDY

This study was carried out in the Nangka watershed, which is located in the island of Lombok of West Nusa Tenggara province, Indonesia (Fig. 1). The basin has an area of 32.87 km^2 and is characterised by its function as a high utility river with the purpose for agriculture, domestic water supply, and traditional fishponds [NT I RBO 2013]. Land use is closely related to elevation and topography, dominated by forests, ricefields, and residential areas (see Fig. 2). The river has a very steep bed slope in the upstream part and is relatively plain in the lower course. These natural factors cause severe soil disturbance in the form of soil erosion and other various environmental problems such as eutrophication of water bodies and water shortages in the irrigation sector causing a serious problem for sustainable agriculture. Combined with unfavourable natural factors such as concentrated heavy rains, land resources have been disturbed, contributing largely to negative impacts such as flooding and deposition in the downstream area [NT I RBO 2013].

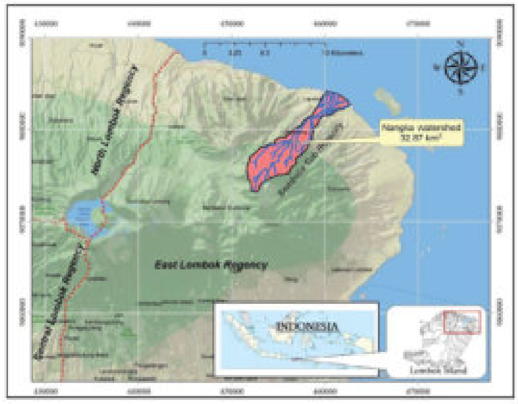

Fig. 1. Location of the study; source: own elaboration

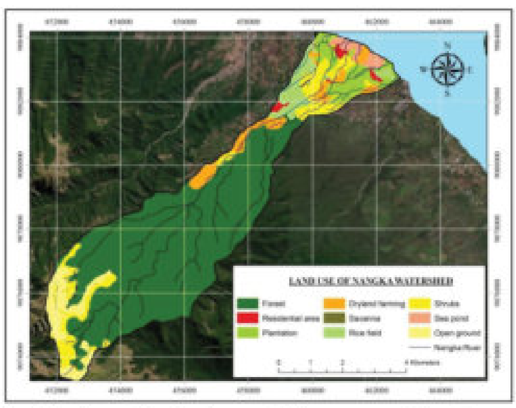

Fig. 2. Land use of the Nangka watershed; source: own elaboration

EROSION ASSESSMENT

Soil erosion is the removal of topsoil mainly caused by water and wind. It is the result of complicated interactions of numerous parameters, including vegetation, climate, topography, and human activities on natural resources [RIZEEI *et al.* 2016] and soil properties. There are five factors that cause erosion and affect the magnitude of the erosion rate, namely climate, soil, topography, vegetation, and human cover [ARSYAD 1989]. Potential erosion is calculated by considering the amount of erosion seen from two factors, rain erosivity and erodibility. Erosivity is the power of rain to cause erosion, while erodibility is the sensitivity of soil to erosion. Water soil erosion is probably one of the most severe natural hazards that remove the fertile and well-organised soil in the catchment area, particularly in the humid region [Rizeei *et al.* 2016].

The common empirical model used for assessing and predicting soil erosion is the universal soil loss equation (USLE), which was originally developed by Wischmeier and Smith [1978]. USLE was modified into the revised universal soil loss equation (RUSLE) [McCool *et al.* 1995; Renard *et al.* 1991] with an adaptation of the input factors to the local conditions [Gashaw *et al.* 2017]. A review by Pandey *et al.* [2021] suggested that the RUSLE model has been widely used although RUSLE has its limitations, it only accounts for soil loss through sheet and rill erosion and ignores the effects of gully erosion and dispersive soils [Rowlands 2019]. In comparison to other conceptual and process-based models, RUSLE has relatively simple computational input requirements [Gashaw *et al.* 2017]. Supported by the development of information technology, GIS methods are used to identify and compute USLE or RUSLE factors to assess soil erosion.

In this study, the input factors of the RUSLE model were adapted to the Nangka watershed condition. The model will be helpful in formulating appropriate soil conservation and management plans [Srinivasan *et al.* 2021] and it has the advantage of simple data processing, making it easy to calculate manually or using computer program tools. RUSLE employed the same factorial approach as USLE [Lee *et al.* 2017] in the form of the following equation:

$$A = R \cdot LS \cdot K \cdot CP \tag{1}$$

where: A = erosion rate in Mg·ha^{-1}·y^{-1}, R = rainfall erosivity factor, LS = topographic factor that includes L = slope length and S = slope steepness, K = soil erodibility factor reflecting the susceptibility of a specific soil to erosion, CP = C = land use factor and P = conservation practice or land management factor.

Identification of areas vulnerable to soil erosion is crucial in applying soil conservation measures, especially in the watershed. Long-term predictions of rainfall erosion in relation to land management using the USLE and RUSLE modelling approaches must take into account the geographic variations in soil loss associated with climate and soil [Kinnell 2014]. A common problem such as the lack of rainfall intensity data should also be anticipated. In this study, the rainfall data used to determine the value of the erosivity (R) factor are the average annual rainfall, the average of rainy days per year, and the monthly average of maximum daily rainfall.

The formula used in calculating the R factor is given by Bols [1978] who collected 38 years of recorded monthly rainfall data from 47 stations on the island of Java, Indonesia. The formula is expressed as follows:

$$R = 6.12(RAIN)^{1.21} \cdot (DAYS)^{-0.47} \cdot (MAXP)^{0.53} \tag{2}$$

where R = rainfall erosivity factor, $RAIN$ = average annual rainfall, $DAYS$ = average rainy days per year, $MAXP$ = average maximum rainfall within 24 hours per month over the period of one year.

The topographic factor defined by Wischmeier and Smith [1978] is a combination of slope length (L) and the steepness of the slope (S) factors. Both factors substantially affect the rate of soil erosion [Gashaw *et al.* 2017]. The greater value of the slope generates a higher level of erosion than that of the flatter surface.

Erodibility of the soil (K) indicates the level of soil sensitivity to erosion. It is influenced by soil texture, i.e. percentage of very fine sand, silt and clay, soil structure, soil permeability, and the organic content of the soil. Among the most commonly used methods in determining the K factor, there is the soil nomograph [Wischmeier, Smith 1978] which uses a relative proportion of soil texture and structure, permeability, and organic content [Gashaw *et al.* 2017].

In determining the land use (C) factor and conservation practice or land management (P) factor, the required data is land use or land cover data and the existence of conservation in the Nangka watershed. The C factor illustrates the relative effectiveness of crop and soil management practices on soil erosion prevention [Lee *et al.* 2017]. According to Wischmeier and Smith [1978], the C factor represents the interrelated effects of crop type, the sequence of the crop, cultural practices, and the growing period. The C factor is basically a numerical description to compare the rate of soil erosion of particular farmland with the associated losses from fallow and cultivable land [Lee *et al.* 2017]. This factor measures the combination of plant influence and its management.

The value of C is a very complicated factor and is influenced by many variables [Arsyad 1989]. Influential variables can be assembled into two groups namely natural variables and variables that are influenced by the management system. The main natural variables are climate and plant growth phase, while the group of variables that are affected by the management system is plant canopy, the mulch of plant remnants, plant remnants buried in the soil, tillage, the effect of soil management residuals, and interactions between variables [Arsyad 1989].

The human intervention factor in soil conservation (P) is the relationship between the amounts of erosion from the land with a particular conservation action to the amounts of erosion on the land without any conservation action. The P factor reflects the effects of practices on the reduction of water runoff and soil erosion [Lee *et al.* 2017].

In this study, the values of LS, K, and CP factors were adopted and determined based on the guidelines and publication of soil conservation practices in Indonesia published by the authority, i.e. Ministry of Forestry Regulation No. P.32/MEN-HUT-II/2009 regarding the guidelines for planning arrangement of forest and watershed rehabilitation techniques for LS and CP values [MKRI 2009] and Soil Research Institute (Ind.: Balai Penelitian Tanah) for K values [BPT 1985] respectively.

EROSION HAZARD LEVEL

A potential danger of soil erosion is classified by utilising the characteristic of soil erosion. The classification is based on severity classes. The classes can be different depending on the criteria issued by the local or national authorities [Gashaw *et al.* 2017; Saadi *et al.* 2010; Srinivasan *et al.* 2021; Vijith, Dodge-Wan 2020]. In this study the potential danger of soil erosion has been classified based on the criteria stated in Ministry of Forestry of Republic of Indonesia (Ind.: Menteri Kehutanan Republik Indonesia – MKRI) [2009]. The criteria are shown in Table 1.

Table 1. The criteria of erosion hazard level

Erosion class	Soil loss ($Mg \cdot ha^{-1} \cdot y^{-1}$)	Erosion hazard level
I	≤15	very low
II	(15–60⟩	low
III	(60–180⟩	medium
IV	(180–480⟩	severe
V	>480	very severe

Source: own elaboration based on MKRI [2009].

RESULTS AND DISCUSSION

RAINFALL EROSIVITY (*R*) FACTOR

Three nearest automatic rainfall recorder (ARR) stations from the Nangka watershed were selected, and the weight at each rainfall station, in proportion to the watershed area that is closest to the rainfall station, was defined by using the Thiessen polygon method (Fig. 3). By constructing the polygon, two out of three ARR stations were determined to have an influence on the Nangka watershed (shown in Fig. 4). Data obtained from two ARR stations is presented in Table 2.

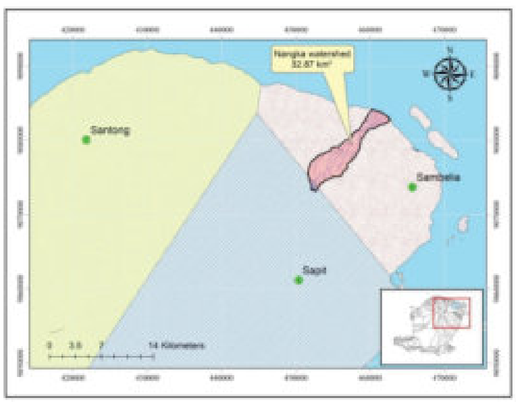

Fig. 3. The nearest automatic rainfall recorder stations from the Nangka watershed; source: own elaboration

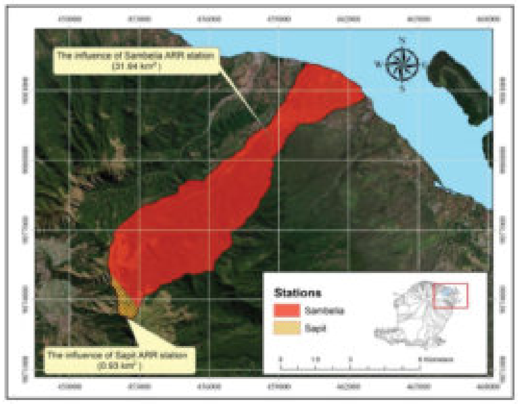

Fig. 4. The area assigned to the two automatic rainfall recorder stations within the Nangka watershed; source: own elaboration

Table 2. Rainfall erosivity factor of two automatic rainfall recorder stations located in the neighbourhood of the Nangka watershed

ARR stations	Rainfall (cm)	Maximum rainfall (cm)	Rainy days (d)	Rainfall erosivity (*R*) factor
Sapit	157.530	7.950	133.760	850.590
Sambelia	101.560	7.010	56.000	704.380

Explanations: ARR = automatic rainfall recorder.
Source: own study.

SOIL ERODIBILITY (*K*) FACTOR

The types of soil in the Nangka watershed are shown in Figure 5. The reddish brown Mediterranean with a percentage of 47.247% dominates the soil, followed by the association of brown latosols and reddish brown latosols (38.850%), greyish brown alluvial (13.873%) and brown Regosols (0.030%). The *K* factor described in Table 3 was determined based on the table, published by the Soil Research Institute (Ind.: Balai Penelitian Tanah) in Bogor [BPT 1985], which contains the value of the erodibility factor for each type of soil in Indonesia.

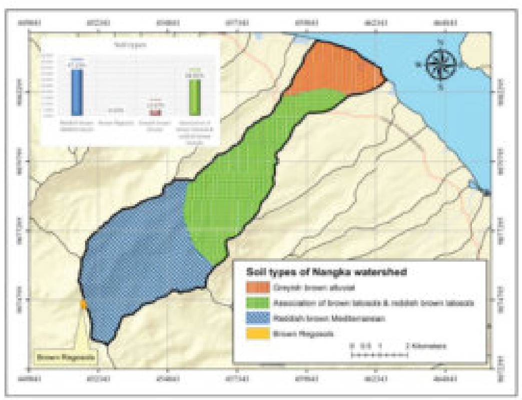

Fig. 5. Soil types in the Nangka watershed; source: own elaboration

Table 3. Soil types and soil erodibility (*K*) factor in the Nangka watershed

Soil types	Area (km^2)	%	*K*
Reddish brown Mediterranean	15.530	47.247	0.323
Brown Regosols	0.010	0.030	0.346
Greyish brown alluvial	4.560	13.873	0.193
Association of brown latosols and reddish brown latosols	12.770	38.850	0.251

Source: own study.

LAND USE (*C*) FACTOR AND CONSERVATION PRACTICE (*P*) FACTOR

The required data for land use (*C*) factor and conservation practice (*P*) factor is the land use data and the existence of conservation. The spatial distribution of the land use in Nangka watershed is presented in Figure 2, whereas the *CP* values for different land cover are shown in Table 4. These values were adopted from MKRI [2009].

Table 4. Land use and conservation practice (*CP*) factor in the Nangka watershed

C	Area (km^2)	%	*CP* factor
Forest	22.040	67.07	0.03
Residential area	0.170	0.51	0.60
Plantation	1.810	5.51	0.30
Dryland farming	1.730	5.26	0.75
Savanna	0.270	0.82	0.70
Rice field	1.170	3.57	0.05
Shrubs	5.020	15.27	0.10
Sea pond	0.530	1.63	0.05
Open ground	0.120	0.35	0.75

Explanations: *C* = land use, *P* = conservation practice.
Source: own study.

TOPOGRAPHIC (*LS*) FACTOR

In this study, slope maps were obtained from digital elevation model (DEM) data processing using the ArcGIS environment. The analysis resulted in a slope map that is coloured according to the need (Fig. 6). The resulting slope map indicated that the topographic (*LS*) factor varied from 0.25 to 12.00 (Tab. 5).

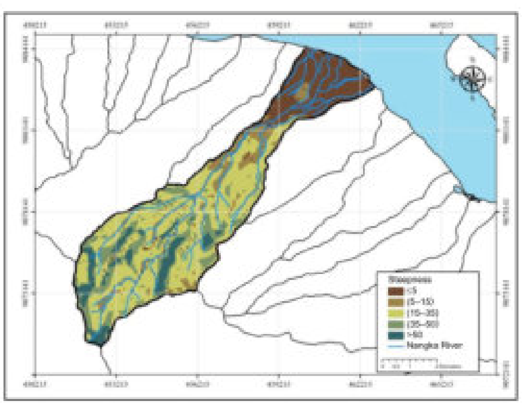

Fig. 6. Slope map of Nangka watershed; source: own elaboration

Nangka watershed is dominated by a slope between (15–35)%, which accounted for 46.36% of the area. It is followed by slope of ≤5% (18.55% of the area), slope between (35–50)% (13.57% of the area), slope between (5–15)% (13.54% of the area), and slope >50% (7.46% of the area) respectively. Conversion of the slope and steepness in the Nangka watershed into topographic (*LS*) factor is adopted from MKRI [2009] and presented in Table 5.

Table 5. Topographic factor (*LS*) in the Nangka watershed

Steepness (%)	Area (%)	*LS* factor
≤5	18.550	0.25
(5–15)	13.540	1.20
(15–35)	46.360	4.25
(35–50)	13.570	9.50
>50	7.460	12.00

Source: own study.

EROSION RATE AND HAZARD LEVEL

The calculation of the erosion was carried out by overlaying all resulting factor maps of *R*, *K*, *LS*, *C*, and *P* into the RUSLE equation. The results are classified into erosion classes on the basis of the erosion hazard map of the Nangka watershed. The resulting calculation of erosion using ArcGIS Desktop suggests that the level of erosion corresponds to the open ground and steepness of the slope in which a very severe erosion of 2472.29 $Mg \cdot ha^{-1} \cdot y^{-1}$ occurs in the upper course with grid number 162, and very low erosion of 1.33 $Mg \cdot ha^{-1} \cdot y^{-1}$ occurs in the downstream of the watershed with grid number 1 (Fig. 7). Soil erosion severity map of the Nangka watershed is presented in Figure 8.

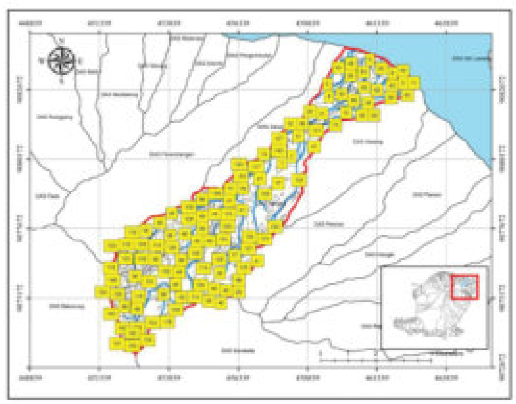

Fig. 7. Overlay grid number; source: own elaboration

The estimation of the erosion hazard level in the Nangka watershed is determined based on the rate of erosion (*A*), which is a calculation of the factors of rain erosivity, soil erodibility, length and slope, land cover, and soil conservation measures. Table 6 presents the results of potential soil loss from the soil erosion severity map (Fig. 8) generated using ArcGIS Desktop. The level of erosion hazard is categorised into five classes as defined by MKRI [2009].

The soil erosion severity map in Figure 8 indicates the sub-watershed, which is prone to erosion. Based on Table 6, soil erosion is low in 50.48% of the area (class II), followed by very low in 25.47% of the area (class I), and moderate in 14.25% of the

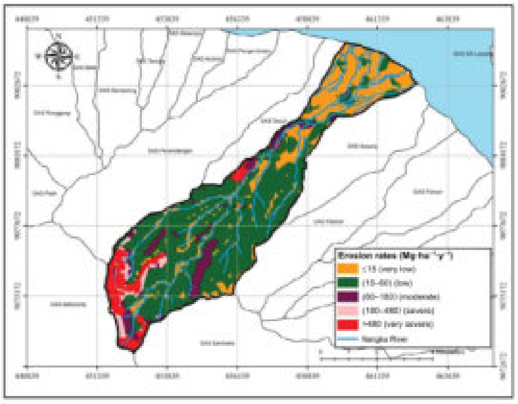

Fig. 8. Soil erosion severity map of the Nangka watershed; source: own elaboration

Table 6. Erosion hazard level in the Nangka watershed

Class of erosion	Erosion (*A*) rate ($Mg \cdot ha^{-1} \cdot y^{-1}$)	Area		Severity class
		km^2	%	
I	≤15	8.37	25.47	very low
II	(15–60)	16.59	50.48	low
III	(60–180)	4.68	14.25	moderate
IV	(180–480)	0.92	2.79	severe
V	>480	2.31	7.01	very severe

Source: own study.

area (class III). Soil erosion is a serious problem in almost 10% of the area of the Nangka watershed with 0.920 km^2 (2.79%) in a severe condition (class IV) and 2.310 km^2 (7.01%) in a very severe condition (class V).

Analysis of erosion (*A*) rates indicates that all factors are directly proportional to the increase in the rate of erosion. Soil erosion tends to be high when *LS* and *C* factors are also high. Land cover and the slope factor have a considerable influence in determining the rate of erosion. A lower rate of erosion is expected at a lower level of steepness as well as in the densely vegetative cover. The rain erosivity (*R*) factor has a smaller range of values than other factors. A high *LS* factor tends to have greater erosion when compared to other factors. The lower *LS* factor reduces the severity of soil erosion and vice versa. Extremely severe erosion is located in the upper course (high *LS*) with the open ground (high *CP*) where the absence of land cover causes rainwater to directly damage the topsoil and increase the carrying capacity of surface runoff.

CONCLUSIONS

The study provides an understanding of the status of soil erosion vulnerability in the Nangka watershed. The average annual soil erosion was quantitatively predicted based on the RUSLE equation. Soil erosion is a serious problem in the Nangka watershed with a variety of erosion (*A*) rates ranging from 1.33 $Mg \cdot ha^{-1} \cdot y^{-1}$ (very low erosion) to 2472.29 $Mg \cdot ha^{-1} \cdot y^{-1}$ (very severe erosion). As set by the national authority, the basis of soil conservation prioritisations in the entire watershed is categorised into five different erosion hazard classes – very low, low, moderate, severe and very severe conditions.

The study revealed that an area of 8.37 km^2 has a very low erosion rate ($A \le 15$ $Mg \cdot ha^{-1} \cdot y^{-1}$ or class I), and an area of 16.59 km^2 has a low erosion rate ($15 < A \le 60$ $Mg \cdot ha^{-1} \cdot y^{-1}$ or class II), an area of 4.68 km^2 has a moderate erosion rate ($60 < A \le 180$ $Mg \cdot ha^{-1} \cdot y^{-1}$ or class III), an area of 0.92 km^2 has a severe erosion rate ($180 < A \le 480$ $Mg \cdot ha^{-1} \cdot y^{-1}$ or class IV), and an area of 2.31 km^2 has a very severe erosion rate ($A > 480$ $Mg \cdot ha^{-1} \cdot y^{-1}$ or class V) respectively. Results from this study are of great use for undertaking suitable conservation measures based on the erosion classes. This measure can be applied for erosion risk assessment in watersheds with similar characteristics so that a subsequent priority of conservation measures can be easily determined particularly in susceptible erosion areas.

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