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CONSERVATION OF PINULOT-CAULAMAN RIVER WATERSHED USING GIS AND RUSLE-BASED SOIL EROSION RISK ASSESSMENT IN CENTRAL LUZON, PHILIPPINES

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07 March 2025

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07 March 2025

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DECLARATION

This is to certify that:

I. The special problem comprises only my original work towards the MENRM except where indicated in the Preface

II. Due acknowledgment has been made in the text to all other material used

III. The special problem is fewer than 25,000 words in length, exclusive of tables, maps, bibliographies and appendices.

CARLO P. SALAC
Name

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TABLE OF CONTENTS

List of Tables

List of Figures

Abstract

Soil erosion is a serious environmental issue which can drastically impact watersheds like the case of Pinulot-Caulaman River Watershed (PCRW) in Central Luzon, Philippines. PCRW is a critical watershed for agricultural and domestic purposes covering Zambales Range and Mt. Natib to the west and lowland areas to the east. This study investigated the biophysical and socioeconomic conditions of PCRW to estimate the overall soil erosion risk and recommend conservation strategies appropriate for the watershed. The methodology involved data mining online and processing of secondary information through Geographic Information System (GIS). This was followed by applying Revised Universal Soil Loss Equation (RUSLE) model to compute soil erosion and delineate risk zonation by analyzing the temporal and spatial changes in the watershed on three selected periods, i.e., 2014, 2017, and 2024.

The PCRW is characteristically fragmented showing declining forest cover across complex topography with young and clay-rich soil types that received abundant rainfall, however, there were minimal conservation practices employed. Based on RUSLE, soil erosion with more than 300 tons ha^{-1} annually was considered very severe, particularly in steep and sparsely vegetated western areas of the watershed. In 2014, these severely eroded areas covered 20% of PCRW which increased to 28% with 11,696 hectares erosion coverage a decade after. Considering the status of the watershed, these critically erodible areas should be prioritized for restoration through the enhanced National Greening Program (NGP). Furthermore, moderate to very high erosion risk categories require conservation measures while intact forested slopes should be delineated as protected zones that will altogether form part of the watershed management plan.

This study highlighted the applicability of GIS techniques and RUSLE model in providing data-driven and evidence-based decision-making tools for soil conservation. Furthermore, erosion results can be verified through ground validation to enhance the accuracy of the model in assessing the PCRW, together with future watershed assessment of erosion in other parts of the country.

Keywords: *soil erosion risk; RUSLE; GIS; watershed management and conservation*

I. INTRODUCTION

Soil erosion is defined as the process of removing soil particles from one place, then transporting and depositing in another through various media, most notably through water, wind, and human intervention (Koralay & Kara, 2018). In the Philippines, it remains as one, if not the most prominent form of land degradation which occurs on various scales and which poses major environmental and agricultural problems (Medina, 2019). Tropical countries frequented by tropical cyclones and monsoon rains such as the Philippines are particularly vulnerable, as water is the primary agent for soil erosion. Sloping agricultural areas with minimal or denuded vegetative cover are highly vulnerable and make up at least 11.45 million hectares of the country's total land area (David, 1988; Medina, 2019).

The ecological integrity and socioeconomic value of watersheds are continuously threatened by soil erosion. High rates of deforestation, and conversion of forestlands within watersheds into agriculture and built-up areas can exacerbate soil erosion by diminishing the resistance of soil particles against external eroding factors (Coxhead & Jayasuriya, 2004; Koralay & Kara, 2018). Soil erosion also strips away the nutrient-rich topsoil, leading to poorer agricultural yield and less sustainable food security. The lack of tenure and poverty among subsistence farmers eventually compel them to leave the less productive lands and cultivate the highly erodible uplands for sustenance (Medina, 2019). Furthermore, watershed degradation due to soil erosion leads to river siltation which can drastically affect water quality, disrupt aquatic habitats, and aggravate flooding on communities on lowlands and floodplains (Rondal, 2005).

The Pinulot-Caulaman River Watershed (PCRW) in Central Luzon, Philippines, plays a fundamental role in providing sustenance to the local ecosystems and agriculture in the provinces of Bataan, Pampanga, and Zambales (Ejercito, 2016). This watershed hosts several protected areas, and forest reserves and acts as a water source for agriculture and the surrounding communities. However, the impacts of agricultural expansion, land use conversion, and climate change may raise concerns about land degradation within this area.

Soil conservation is an important part of sustainable watershed management, and to that end, studying soil erosion especially for critical watersheds such as PCRW is highly beneficial. The advent of Geographic Information System (GIS) and remote sensing has allowed for massive advancement in landscape and ecological research due to their ability to analyze large volumes of data over a wide range of areas and long periods of time. Moreover, the use of Revised Universal Soil Loss Equation (RUSLE) Model has been widely adopted due to its simple and straightforward computational requirements for the calculation of erosion-induced soil loss (Dapin & Ella, 2023). The use of these techniques can provide a practical and straightforward approach to assessing soil erosion risk in PCRW to improve the management and planning of the watershed.

II. REVIEW OF LITERATURE

The effects of soil erosion in watersheds can drastically alter their ecological and socioeconomic roles. Erosion removes the nutrient-rich topsoil cover, thereby reducing soil productivity for natural vegetation and agriculture. In terms of hydrological processes, soil erosion also impacts downstream due to siltation of rivers and dams/reservoirs, causing damage to aquatic ecosystems and aggravation of flooding (Pimentel et al., 1995). Critical watersheds such as the PCRW, defined as drainage area of river systems that supports existing and planned irrigation works, hydroelectric power, and other water facilities in need of urgent protection and rehabilitation to improve yield and lessen erosion (Ejercito, 2016), are particularly vulnerable to such hazards. For instance, the northern part of PCRW covered by the towns of Floridablanca, Subic, and San Marcelino are heavily devastated by the eruption of Mt. Pinatubo in 1991. Pyroclastic ejecta of catastrophic proportions was deposited along the slopes of several watersheds surrounding the volcano. Continuous erosion of debris from 1992 to 1994 buried the riverbanks, forcing indigenous Ayta communities to evacuate their ancestral homes. Furthermore, the western part of Pampanga province covered by PCRW is declared as part of the Porac-Gumain Growth Center of the Preferred Spatial Development Strategy of the province, which will be intended for cultivation of food and high value crops (Floridablanca Municipal Planning and Development Office [MPDO], 2016). This plan highlights the importance of addressing soil erosion in critical watersheds.

Studies on soil erosion risk employ various methods and models, one of which is the Universal Soil Loss Equation (USLE). Developed by Wischmeier & Smith (1978), USLE incorporates various climatologic, topographic, geologic, and conservation variables into calculating soil loss. Continuous research to improve erosion predictions led to the development of the revised universal soil loss equation (RUSLE), which included land use / land cover (LULC) changes and temporal rainfall variables to the equation. Such modifications greatly expanded the applicability of RUSLE not only in agriculture but also in various land use types (Renard et al., 1997). Furthermore, the advent of Geographic Information System (GIS) and remote sensing has vastly enhanced the applicability of RUSLE in soil erosion studies, with improved spatio-temporal range and accuracy, better management and visualization, and greater versatility and applicability (Pandey et al., 2021).

In the Philippines, GIS-based RUSLE is used for various soil loss research and applications. Alejo et al. (2024) conducted research on the soil erosion at critical watersheds hosting dams such as the Pantabangan-Carranglan Watershed in Central Luzon. They concluded that soil erosion trends increased through time, with annual crop and barren lands having the most contribution to erosion and eventual siltation of the Pantabangan Dam. Moreover, Villas et al. (2023) used RUSLE to determine annual sediment replenishment rates for Bongabong Catchment Area in Oriental Mindoro which is exposed to massive sediment extraction industry such as quarrying.

It is established that GIS and RUSLE are valuable tools for soil erosion assessment and watershed management; however, they have their own limitations and avenues for improvement. As an empirical approach, the accuracy and applicability of the RUSLE model heavily relies on the availability of various data needed at the correct scale and resolution. Inputs such as the rainfall erosivity, soil properties, and conservation practice factors are variables that oftentimes pose difficulty in ascertaining their accuracy. Furthermore, applicability of results on local erosion risk assessment is dependent on the scale of the analysis and resolution of data such as satellite imagery and Digital Elevation Models (Almouctar et al., 2021).

III. STATEMENT OF THE STUDY

This study sees the importance of assessing the interplay of various biophysical and socioeconomic attributes such as topography, climate, land use/cover conversion, and management practices, as well as determining their combined impacts to the soil erosion risk within a watershed. Soil erosion can detrimentally affect the role of a watershed to society in terms of agriculture, irrigation, geohazards, among others. This is particularly crucial for Pinulot-Caulaman River Watershed, one of the considered critical watersheds supporting national irrigation systems in Central Luzon (Ejercito, 2016).

By applying GIS methods and the RUSLE model, this study seeks to generate soil erosion risk maps for the PCRW representing several periods of time, determine soil erosion rates and hotspot areas, and utilize the findings to recommend measures to optimize existing and future watershed management efforts.

IV. OBJECTIVES OF THE STUDY

The main objective of the study is to assess the soil erosion risk within the PCRW which can be utilized as valuable inputs to effective watershed management. Specifically, the study aims to:

1. Characterize the delineated PCRW in terms of its biophysical and socioeconomic attributes;
2. Assess the overall soil erosion risk of PCRW using the generated soil erosion risk maps of the area; and
3. Evaluate results for the development of appropriate conservation measures for the watershed.

V. RATIONALE

The geologic, geomorphological, and climatological setting of the Philippines makes it susceptible to various environmental problems such as soil erosion. This environmental hazard has various negative impacts to the hydrogeological characteristics of watersheds such as, but not limited to change in infiltration rates, loss of organic topsoil, and siltation of natural drainages (Koralay & Kara, 2018). Moreover, watersheds are crucial to agriculture as one of the main sources of irrigation for farmlands. Soil erosion denudes the fertile topsoil, ultimately reducing soil productivity and sustainability. Eroded fine sediments are also deposited along riverbeds and the seas, contributing to siltation of water bodies and downstream flooding (Ahmad et al., 2020).

Apart from sustaining local ecosystems, the PCRW, declared as a critical watershed, supplies irrigation water to various agricultural areas in the provinces of Pampanga, Bataan, and Zambales (Ejercito, 2016). Therefore, there is an increasing importance and urgency to address the possible impacts of soil erosion within the PCRW to prevent further damage to the watershed, the agriculture sector, and receiving communities. However, there are limited comprehensive studies focused on the processes governing PCRW such as soil erosion risk assessment. Thus, the results of this study can contribute to the understanding of soil erosion impacts on a local scale and can serve as additional planning tool towards an effective and sustainable management of PCRW.

VI. SCOPE AND LIMITATIONS

This study focuses mainly on the various attributes of the Pinulot-Caulaman River Watershed in Central Luzon, Philippines within the bounds defined by the Department of Environment and Natural Resources. The information used are secondary data obtained from several local government agencies and international open-source institutions. As such, the cooperation of said agencies affects the scope of this research. For instance, significant secondary data used were obtained from the Department of Environment and Natural Resources (DENR), which is the chief implementor of watershed management. For the Local Government Units (LGUs), Comprehensive Land Use Plans (CLUP) and pertinent maps were obtained, albeit not from all concerned municipalities. Moreover, the accuracy of analysis is limited to the resolution of the GIS data available which ranges from 5 meters to 30 meters. The range of temporal analysis is also limited by the availability of usable satellite imagery, such as those free of cloud cover. For this study, available satellite imageries of the area with acceptable cloud cover were obtained from 2014, 2017, and 2024. In addition, other data required for the calculation factors for the RUSLE model were not readily available and instead were generated using GIS software such as ArcGIS 10.7.1. Furthermore, ground validation for LULC change analysis was not conducted due to unforeseen circumstances on the side of the author. Instead, the accuracy of the LULC change analysis was measured using confusion matrix and statistical methods such as the kappa coefficient.

VII. DESCRIPTION OF THE STUDY AREA

The Pinulot-Caulaman River Watershed (PCRW) is a critical watershed situated on the triple-boundary between the provinces of Pampanga, Bataan, and Zambales on the western portion of Central Luzon. It has an estimated area of 42,084.89 hectares (Ha) as computed using ArcGIS 10.7.1. software. The area of PCRW is within the boundaries of 105 barangays from nine municipalities of three provinces, namely: Dinalupihan, Hermosa, Orani, and Morong in Bataan province, Lubao and Floridablanca in Pampanga province, and Subic, Olongapo City, and San Marcelino in Zambales province (Figure 1). Among these, the towns of Hermosa and Dinalupihan account for 54.4% of the watershed's total land area. The PCRW is characterized by rugged and mountainous topography to the west and south as part of the Zambales Range and Mt. Natib, respectively, with maximum elevation of 958 meters above sea level (masl) and average slope of 22%. The rugged terrain then tapers into gentler lowlands towards the east with numerous drainages converging at the center to form major rivers such as Almacen River, Pinulot River, and Caulaman River (Figure 2). These rivers eventually drain towards Manila Bay to the east. The PCRW also covers portions of several protected areas, including most of Roosevelt Protected Landscape (RPL), upper parts of Bataan Natural Park (BNP), and eastern end of Olongapo Watershed Forest Reserve (OWFR).

Proposed as one of the critical watersheds supporting national irrigation systems (Ejercito, 2016), the PCRW promotes agriculture in these provinces by supplying irrigation water for the numerous farmlands in the area. As a result, the municipalities have also experienced significant growth and land cover change in the past decades. Moreover, towns are currently facing pressing issues on river siltation and flooding whenever there is an overflow along waterways, especially in the Almacen River.

Figure 1. Location Map of Pinulot-Caulaman River Watershed showing the municipalities and protected areas within its area.

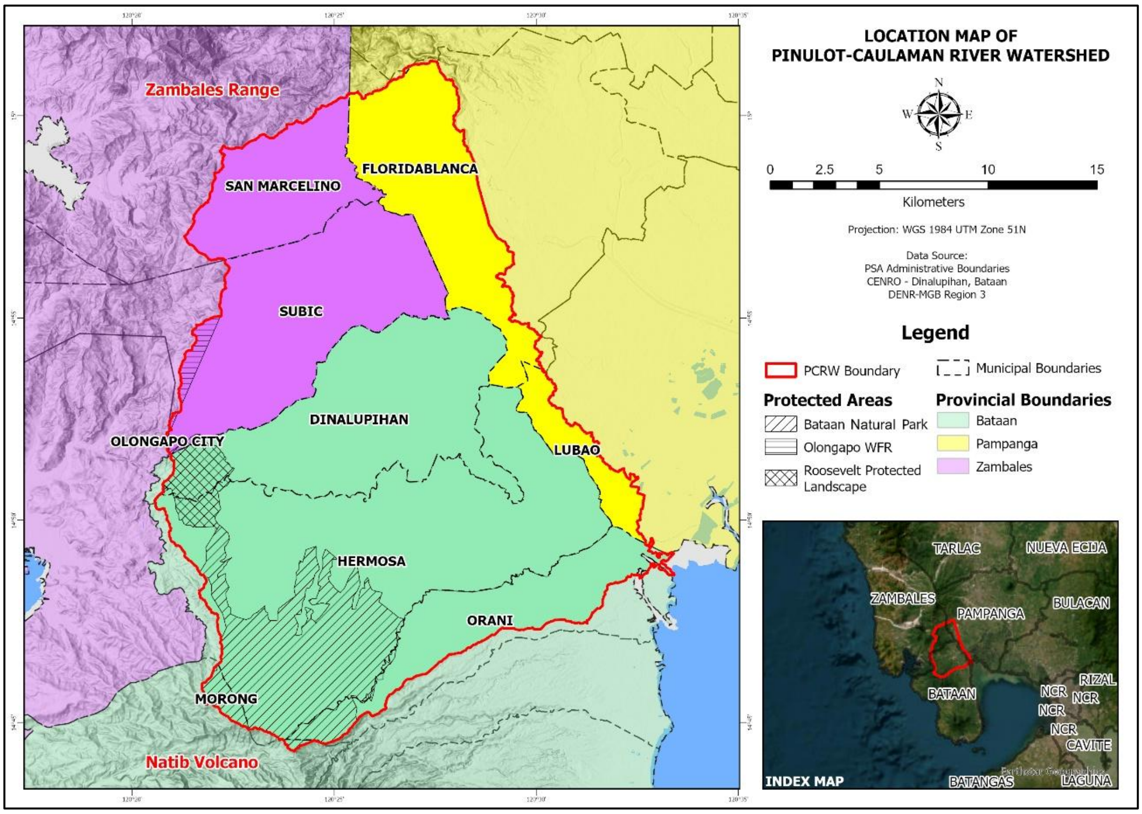
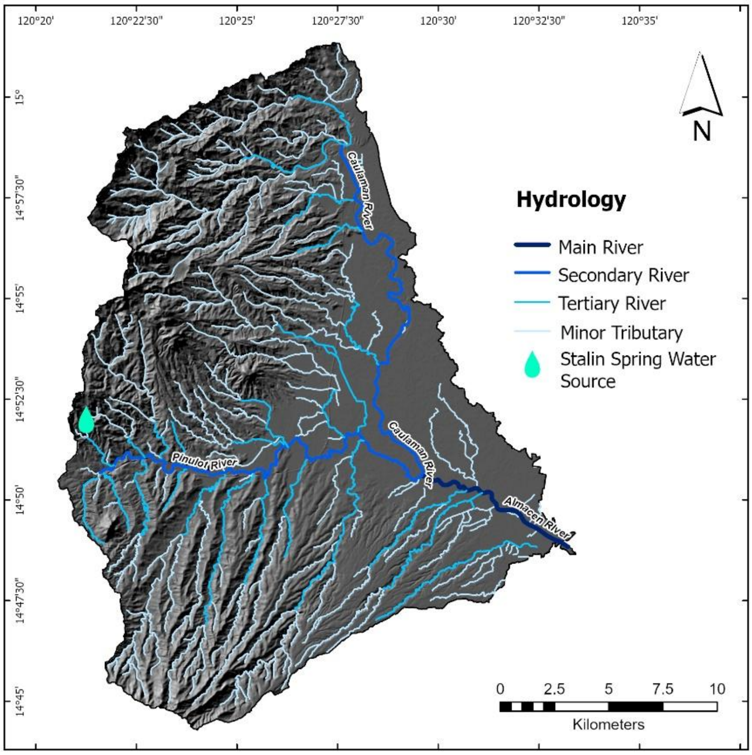


Figure 2. Drainage Map of PCRW showing the major rivers in the area: Pinulot, Caulaman, and Almacen Rivers.

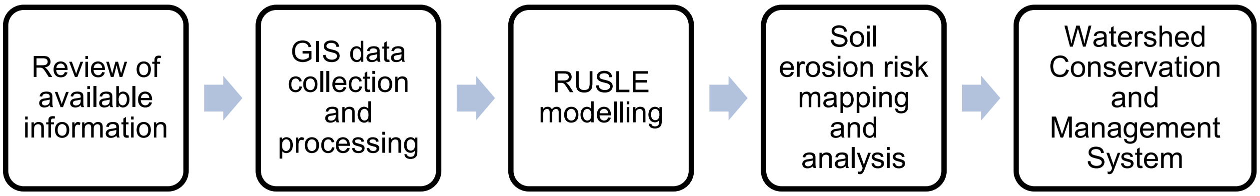


VIII. METHODOLOGY

Research Framework

This assessment of soil erosion risk within the PCRW was primarily done in a quantitative approach using GIS, remote sensing, and RUSLE models. Moreover, temporal analysis of LULC changes was integrated in the process to effectively correlate land cover change and soil erosion level. Thus, the whole research process was divided into five phases, namely: (1) review of available information, (2) GIS data collection and processing, (3) RUSLE modelling, (4) soil erosion risk mapping and analysis, and (5) watershed conservation and management system.

Figure 3. Research framework for the soil erosion risk assessment of PCRW using GIS methods and RUSLE model.



Review of available Information

Information on the biophysical and socioeconomic attributes, as well as existing management plans, if any, were sourced from various national government agencies (NGAs) and local government units with areas of jurisdiction within the PCRW. These NGAs include the provincial offices of the Department of Environment and Natural Resources (DENR), National Commission on Indigenous Peoples (NCIP), and Bureau of Soils and Water Management (BSWM). In particular, the proposed Integrated Watershed Management Plan (IWMP) of the Community Environment and Natural Resources Office - Dinalupihan (2021) was used as a significant source of information for this study. Other types of information that were acquired from these institutions include location and status of National Greening Program (NGP) reforestation sites, protected area management plan, comprehensive land use plans (CLUP) and socioeconomic profiles of LGUs concerned with the PCRW, among other available plans and data. The data used for this study and their sources are summarized in Table 1.

Table 1

Summary of Data Used and their Respective Sources

Type of Data	Methods of Data Collection	Sources
Rainfall	Secondary; GIS-generated	PAGASA ; NASA Power Project
Soil Type	Secondary	BSWM (1993, 2013); Carating et al. (2014); PhilRice (2010, 2013a, 2013b)
Slope	GIS-generated	DEM from MGB (2014)
Land Use / Cover	GIS-generated	LandSat-8 (2014); Sentinel-2 (2017, 2024)
Bioecological profile	Secondary	CENRO-Dinalupihan (2021)
Socioeconomic and Demographic profile	Secondary	CENRO-Dinalupihan (2021);
Management Data	Secondary	PAMO-BNP (2021) CENRO-Dinalupihan (2021); Floridablanca-MPDO (2016); Dinalupihan-MPDO (2019); Orani-MPDO (2019); San Marcelino-MPDO (2018)
NGP Data	Secondary	CENRO-Dinalupihan
CADT Data	Secondary	NCIP (2015)

GIS Data Collection and Processing

Aside from the characterization of the biophysical and socio-economic aspects of the watershed, the abovementioned data are also useful as the RUSLE model uses various types of geospatial, climatological, soil, and land use/cover data. Digital Elevation Model (DEM) at 5-meter cell resolution derived from Interferometric Synthetic Aperture Radar (IFSAR) from the Mines and Geosciences Bureau (2014) was used to calculate slope characteristics. For the LULC data, LANDSAT and Sentinel Program satellite imagery from USGS Earth Explorer (2014) and Copernicus Open Access Hub (European Space Agency, 2017, 2024), respectively, were utilized. For the annual precipitation data, climatological averages were obtained from the Philippine Atmospheric, Geophysical, and Astronomical Services Administration (PAGASA) (n.d.). In the absence of suitable local weather station inside the study area, annual rainfall averages were sourced from the National Aeronautics and Space Administration (NASA) Langley Research Center (LaRC) POWER Project funded through the NASA Earth Science/Applied Science Program (NASA Langley Research Center, n.d.). Soil type data were obtained from the BSWM through the Geoportal Philippines Website (1993, 2013). Other parameters needed for the RUSLE calculation were generated using the abovementioned data through the ArcGIS 10.7.1 software.

Rainfall erosivity factor, R

The R factor concerns the effect of rainfall impact to the soil, as well as the rate and amount of runoff directly related to the erosion potential of rainfall (Ghosal & Das Bhattacharya, 2020). Following the formula used by Adornado et al. (2009) for R,

$$R = 38.5 + 0.35P \tag{1}$$

where P is the mean annual rainfall (mm). The conventional unit for R factor is MJ mm/ha h yr. Values for the mean annual precipitation were primarily obtained from climatological data of selected monitoring stations of PAGASA (n.d.). However, there are no weather stations established within the area covered by PCRW, instead, average annual rainfall data from five nearest PAGASA stations were utilized, namely: Cubi Point (1994-2020 data) and Iba (1991-2020 data) in Zambales, Clark in Pampanga (1997-2020 data), Port Area in Manila City (1991-2020 data), and Science Garden in Quezon City (1991-2020 data). Moreover, local data were supplemented by annual rainfall data obtained from the

NASA POWER project, which utilizes the agency's MERRA-2 meteorological datasets (NASA LaRC, n.d.). It should also be noted that since the data presented are the total rainfall amount in a year averaging over at least the last 23 years, they also account for extreme weather events that have occurred in the region over the same timeframe. These include, but not limited to, Tropical Cyclones *Diding* in 1991 which caused the catastrophic lahars following the Pinatubo eruption, *Milenyo* in 2006, *Ondoy* in 2009, *Yolanda* in 2013, *Glenda* in 2014, *Lando* in 2015, *Ulysses* in 2020, among other weather extremes (Hilotin, 2023). The mean annual rainfall for the whole watershed was interpolated through ArcGIS 10.7.1 using the inverse distance weighting (IDW) function. Then, the R factor was calculated using equation (1).

Soil erodibility factor, K

Connected to the R factor is the K factor which measures the soil resistance against the erosive energy of rainfall under a standard condition. This parameter is dependent on the geology and features of the soil such as structures, texture, type of material, porosity, organic matter, among others (Ghosal & Das Bhattacharya, 2020). Soil types for the PCRW were obtained from the BSWM (1993, 2013), Carating et al. (2014), and the Philippine Rice Research Institute (2010, 2013a, 2013b). The soil types were then converted to corresponding K factor values for various Philippine soils based on the works of Stewart et al. (1975) and David (1988). Once reclassified, GIS functions were used to generate the K factor raster layer. The K factor values used in this study, in t ha h/ha MJ mm, are presented in Table 2.

Table 2

Corresponding K factor for various Philippine Soil Types. Adopted from Stewart et al. (1975) and David (1988)

Soil Series	Soil Texture	K factor
Antipolo Soils	undifferentiated	0.3
Antipolo Clay	clay	0.26
Culis Loam	loam	0.38
La Paz Fine Sand	fine sand	0.14
La Paz Silt Loam	silt loam	0.6
La Paz Fine Sandy Loam	sandy loam	0.3
Angeles Fine Sand	fine sand	0.14
Angeles Soil	undifferentiated	0.3
Hydrosol	clay loam	0.22
Mountain Soil	undifferentiated	0.26

Slope – length (L) and steepness (S) factor

These connected parameters represent the contribution of topography to soil erosion rates. Slope length possesses a direct relationship with the amount and rate of cumulative runoff. Similarly, runoff velocity increases with higher slope steepness (Ghosal & Das Bhattacharya, 2020). The formula for LS factor used by Moore & Burch (1986), Adornado et al. (2009), and Dapin & Ella (2023) was adopted in this study:

$$LS = (m + 1) \left(\frac{A}{22.13}\right)^m \left(\frac{\sin(\theta)}{0.0896}\right)^n \qquad (2)$$

where A is the upslope contributing area per unit contour width computed by multiplying flow accumulation and DEM cell size, θ is the slope angle in radians, and m and n are parameters dependent on the prevailing type of erosion. For this study, m = 0.4 and n = 1.3 were adopted based on a similar study of Dapin & Ella (2023) in Bukidnon Province. Therefore, the required input data for LS factor was the 5-meter resolution IFSAR DEM (MGB, 2014) and Raster Calculator was used to create the LS Factor raster layer.

Conservation or Support practice factor, P

The conservation or support practice factor (P) represents soil erosion rate reduction due to runoff rate and volume drop from introduction of various conservation measures (Ghosal & Das Bhattacharya, 2020). Several interventions can be considered, such as contour farming, mulching, and terracing. However, such data are normally obtained on a local level and are oftentimes not readily available. In this case, this study adopted the work done by Yigez et al. (2021) which relates P factor with land cover type and slope steepness. A P factor raster map was generated after reclassifying data based on the conversion matrix for P factor as presented in Table 2.

Cover management factor, C

C factor presents variation on land cover and is an important parameter for soil erosion assessment. Vegetation cover, or any kind of soil cover for that matter, can affect the impact of raindrops to the soil, thus reducing its kinetic energy (Villas et al., 2023). For this study, LULC classification was conducted and corresponding C factor values for each land use class were assigned based on the studies of David (1988) and 1972 guidelines of USDA-Soil Conservation Service (Ghosal & Das Bhattacharya, 2020). Table 4 provides the description of the six land cover classifications used in the LULC analysis, as well as the corresponding C factor values used in this study per land cover category. A C- factor raster layer for the PCRW was generated based on these values.

Table 3

P Factor Values for various Land Use Type and Slope Percent (Wischmeier & Smith, 1978)

Land Use Type	Slope (%)	P factor value
Agricultural Land	0-5	0.10
	5-10	0.12
	10-20	0.14
	20-30	0.19
	30-50	0.25
	50-100	0.33
Other land use type (FL, SRL, GL, BL)	All	1.0
Built-up Areas and Water bodies	All	0

Note: FL – forestlands, SRL – shrub lands, GL- grasslands, BL – barren lands

Table 4

Description of Land Cover Classifications used and corresponding C Factor Values (based on USDA Soil Conservation Service, 1972 and David, 1988)

Land Use / Cover Type	Description	C Factor
Water Body	Rivers, inland waters, fishponds, estuaries	0.000
Built-up Area	Residential, commercial, industrial, road networks	0.000
Forestlands	Natural/Protection forests – dipterocarp, mossy, old and secondary growth; Production forests – for agroforestry; sporadic patches of timber plantation, perennial crops	0.004
Grasslands / Shrublands	Natural upland grasslands and pasture areas, abandoned farmlands, sparse vegetation areas	0.300
Agricultural Lands	Rice, corn, sugarcane, root crops, leafy vegetables	0.400
Barren Lands	Open areas, bare soils, burned down areas	1.000

Temporal Analysis of LULC. This part involves analyzing change in LULC over different time periods to understand the evolution of LULC change in the area, improve analysis of soil erosion risk based on these trends, and provide evidence-based soil conservation recommendations. For this study, satellite images for three time periods from 2014, 2017, and 2024 were used. The type of satellite image to be used and the specific periods largely depended on the availability of high-quality images with minimal cloud cover. Table 5 summarized the details for the satellite images used. Supervised classification of LULC was done for each time period and corresponding LULC maps were generated using ArcGIS 10.7.1. Furthermore, change detection analysis was used to quantify the changes in land cover types for all time periods.

Table 5

Summary of Satellite Images used for LULC Analysis

Date of Satellite Image	Data Source	Cell Size
February 7, 2014	Landsat - 8	30 m x 30 m
April 13, 2017	Sentinel - 2	10 m x 10 m
April 16, 2024	Sentinel - 2	10 m x 10 m

To assess the accuracy of generated LULC maps for different time periods, these were validated by generating a confusion matrix and Kappa coefficient, comparing predicted land cover classes with reference points of known land cover type (Kerbe et al., 2023). Reference points for validation were obtained from high resolution satellite imagery such as from Google Earth Pro. From the confusion matrix, the corresponding Kappa coefficient was produced, and the agreement of the generated LULC maps with the reference data was assessed.

Generation of multiple C Factor raster layers. To improve the resulting analysis, a corresponding C factor map for PCRW was produced for each period used in the LULC temporal analysis (e.g. 2014, 2017, and 2024). These C factor raster layers were then used to generate time-series soil erosion risk maps.

RUSLE modelling

To determine the degree of soil erosion, the needed data were prepared and computed using a GIS software such as ArcGIS 10.7.1, following the RUSLE formula as presented in the Agriculture Handbook No. 537 of the U.S. Department of Agriculture (Wischmeier & Smith, 1978):

$$A = R \times K \times L \times S \times C \times P \tag{3}$$

where, A is the computed average annual soil loss per unit area usually expressed as tons per hectare per year (t/ha/year), R is the rainfall erosivity factor, K is the soil erodibility factor, L is the slope – length factor, S is the slope – steepness factor, C is the cover management factor, and P is the conservation or support practice factor. A corresponding raster layer for each of the needed parameters in the formula was prepared, and then the Raster Calculator function was used to integrate them and produce an annual soil loss map for the entirety of PCRW.

The USLE model and subsequent models derived from it, including the RUSLE model used in this study, are globally accepted methods for estimating baseline erosion in a watershed, and they are used in different geographic conditions and climate type due to their relative simplicity and low data requirements compared to other soil loss models. However, unlike the original USLE method with its limited applicability to complex topography, the RUSLE method can accommodate various forms of terrain with the advancements in GIS software and digital elevation models (Benavidez et al., 2018). Furthermore, there are different methods of derivation of parameters for the RUSLE model, and those used for this study were patterned to account for the tropical climate and complex topography of the Philippines. For instance, the availability of finer-resolution DEM (i.e. 5-m scale) for this study and the relatively small study area allowed the use of flow accumulation to account for the LS-factor (Benavidez et al., 2018). In terms of R-factor, the formula used by Adornado et al. (2009) which is tailored for the Philippine climate was adopted in this study. The same was true for the K-factor computation method which was adopted from the works of David (1988).

Soil Erosion Risk Mapping and Analysis

After computing the annual soil loss rates for the PCRW, the corresponding soil erosion risk maps were generated by employing the soil erosion risk classification used by Dapin & Ella (2023) in their related study in Bukidnon, Philippines. These metrics were chosen based on general similarity of topographic and climatological conditions as compared to classifications used in other international literature. Soil erosion rates were reclassified using these metrics to produce a soil erosion risk map of PCRW. Table 6 presents the risk classification which was used and corresponding soil loss rates. Using the soil erosion risk map, key areas such as soil erosion hotspots can be identified and quantified.

Furthermore, soil erosion risk maps were generated for each selected period (e.g. 2014, 2017, 2024) using similar outputs from the RUSLE model but varying P and C factor raster layers. A change detection analysis using ArcGIS 10.7.1 was conducted to quantify erosion areas per land use type and per risk category. Furthermore, temporal analysis of erosion risk was done to assess any trends on the evolution of erosion hotspots (e.g. increasing, decreasing, retained, change in location, etc.).

Figure 4 presents the general flow of methods from data collection and processing up to the generation of soil erosion risk maps.

Watershed Conservation and Management System

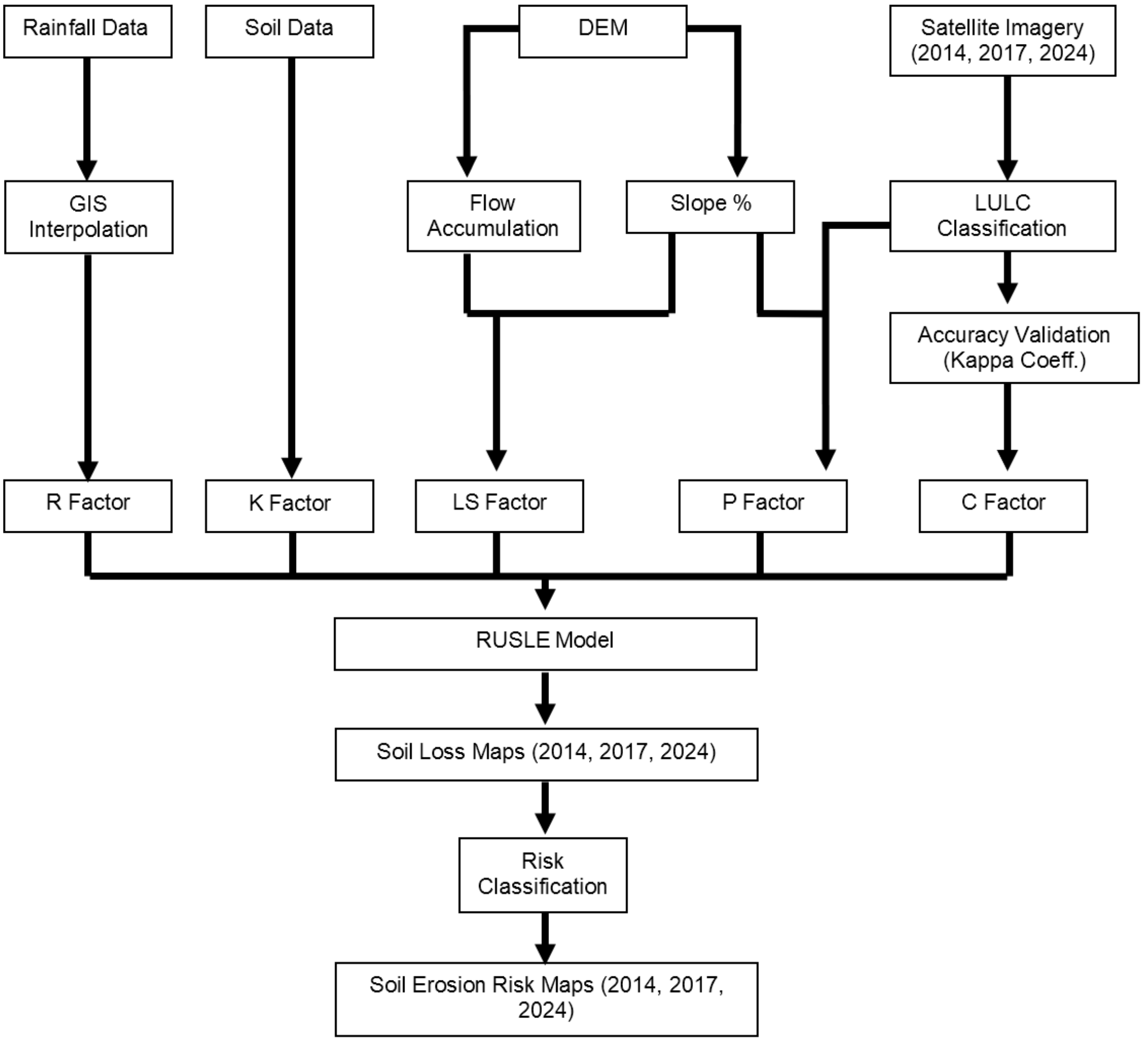
For this study, the analysis of conservation and management strategies for the PCRW was focused on three main categories, namely: Watershed and Protected Areas Management Plans, National Greening Program, and Local Government Units.

Table 6

Classification of Soil Erosion Rates into Soil Erosion Risk Categories. Modified from Dapin & Ella (2023)

Category	Soil erosion rate (t/ha/year)
Very Low to Low	0-5
Moderate	5-15
High	15-50
Very High	50-150
Severe	150-300
Very Severe	>300

Figure 4. General flowchart for the generation of soil erosion risk maps using RUSLE model and GIS techniques.



Watershed and Protected Areas Management Plans

The content of the proposed IWMP and protected areas management plan from the DENR were analyzed in relation to their adequacy in terms of soil conservation and erosion management. Aside from this, the documents also provided information on existing management bodies of the DENR and the linkages between the government and stakeholders in terms of watershed and protected area conservation.

National Greening Program (NGP)

The NGP is one of the main conservation programs enacted primarily by the DENR within the PCRW. For this part, the coverage of the NGP was analyzed in comparison with the results of the soil erosion risk maps to determine trends in the soil erosion risk within established NGP sites. Said analysis was also used to determine the efficacy of citing of NGP areas in covering soil erosion hotspots.

Local Government Units (LGUs)

Finally, this part focused on determining the plans and programs of LGUs in relation to the conservation and management of PCRW. Using the information from CLUPs provided by several of the LGUs concerned, the strengths and gaps in the local plans and programs, especially in terms of soil erosion management, were determined.

IX. RESULTS

Watershed Characteristics

Physical Attributes

Based on the data from the CENRO-Dinalupihan (2021) and verified using ArcGIS 10.7.1. software, the PCRW has an estimated land area of 42,084.89 hectares (Ha) generally classified as Alienable and Disposable (67.16%), Timberlands (17.83%), Protected Area (13.53%), and Military Reservation (1.488%). It is characterized by rugged and mountainous topography to the west and south as part of the Zambales Range and Mt. Natib, respectively. In terms of elevation, at least 70% of the total land area is situated on or below 200 meters above sea level (masl) (Table 7, Figure 5). This constitutes the eastern lowlands and central valleys, as well as the footslopes of PCRW. Mean elevation is recorded at 295 masl while maximum elevation of 958 masl is situated on the mountains of Morong, Bataan. The low-elevation areas to the east also constitute the level to gently sloping terrain, where 44% of the total area have slopes of 0-8%. Average slope in PCRW is about 22%, while 11% of the total area have very steep to severely steep slopes (>30%) representing the mountain ranges on the west and south of PCRW (Table 8, Figure 8A).

In total, the PCRW has a total of 664 km of river systems. The drainages on the upland area of PCRW generally form a radial pattern emanating from the topographic highs of Mt. Natib and Zambales Range. Towards the lowlands, the drainages merge to form the major rivers such as Almacen River, Pinulot River, and Caulaman River. These rivers eventually drain towards Manila Bay to the east (Figure 2).

Table 7

Elevation Distribution within PCRW

Elevation (masl)	Area	
	Hectarage	**Percentage**
0-200	29,692.45	70.55
200-400	8,036.16	19.10
400-600	3,094.84	7.35
600-800	1,093.83	2.60
>800	167.60	0.40
Total	**42,084.89**	**100.00**

Table 8

Slope Classification within PCRW

Slope Category	Slope Range (%)	Area	
		Hectarage	**Percentage**
Level to Gently Sloping	0-8	18,649.33	44.32
Moderate	8-18	10,720.01	25.48
Steep	18-30	8,176.15	19.42
Very Steep	30-50	3,768.50	8.95
Severely Steep	>50	770.90	1.83
	Total:	**42,084.89**	**100.00**

Biological Attributes

The PCRW also covers portions of three protected areas and forest reserves, including the majority of Roosevelt Protected Landscape (RPL), northern parts of Bataan Natural Park (BNP), and eastern end of Olongapo Watershed Forest Reserve (OWFR). Actual transect monitoring assessment of CENRO-Dinalupihan in 2021 concluded that there are no specific biodiversity hotspot areas within the watershed. Despite this, the PCRW is still home to various species of flora and fauna, some of which are considered endemic.

The forestlands within the watershed are mostly classified as young secondary forests, with few remaining fragmented patches of natural old growth forests. The area has forest density of 216.67 tree species per hectare or 141.59 cubic meter of trees per hectare (CENRO-Dinalupihan, 2021). Recent flora composition assessment showed an estimate of 78 tree species belonging to 10 families. Table 9 shows a summary of plant families present within PCRW and their relative distribution. Among these, the family Fabaceae accounts for the majority of the identified plant species at 25.64%. These include familiar species such as Narra, Kakauate, Fringon, Akleng Parang, and Ipil-ipil. However, in terms of individual species count, Gmelina trees (*Gmelina arborea*) are the most common in the area with about 20.51% distribution, followed by Mango and Narra trees at 10.26% and 6.4% distribution, respectively.

Figure 5. Elevation Map of PCRW (modified from MGB, 2014)

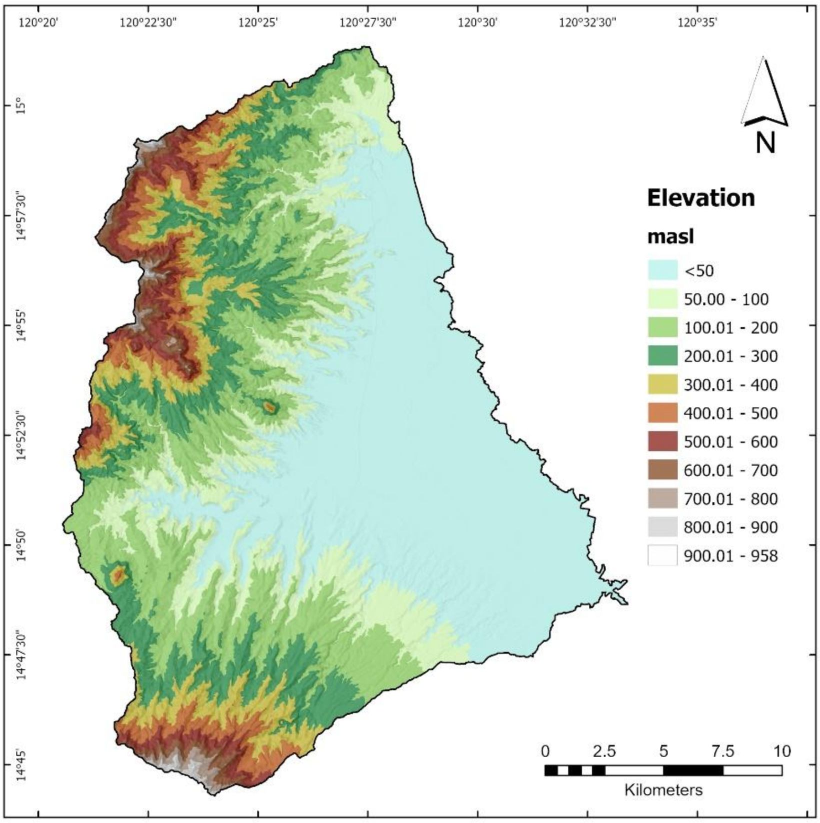


Table 9

Timber Stand Composition and Distribution within PCRW (CENRO-Dinalupihan, 2021)

Plant Family Name	Plant Species (Local Names)	Percent Distribution (%)
Fabaceae	Akleng Parang, Narra, Ipil-ipil, Fringon, Kakauate	25.64
Lamiaceae	Gmelina	20.51
Moraceae	Hauili, Himbabao, India Rubber, Tibig	16.67
Anacardiaceae	Kasoy, Ligas, Mangga	15.38
Euphobiaceae	Banato, Binunga	3.85
Ebenaceae	Bolong eta	2.56
Meliaceae	Santol	2.56
Lythraceae	Banaba	1.28
Canabaceae	Anabiong	1.28
Burseraceae		1.28
Others		8.97
	TOTAL	**100%**

In terms of fauna classification, most of the animal groups found in the PCRW have low to very low diversity except for bird species (Table 10). Roughly 59 species from 30 families of birds were found, most of which are resident and endemic. Some of the most common resident or endemic birds in the area include the Philippine Bulbul, Yellow-vented Bulbul, and Crested Myna. Meanwhile, other bird species such as the Jungle Nightjar and Himalayan Cuckoo are considered migratory (CENRO-Dinalupihan, 2021). Contrary to the birds, the diversity of reptiles, amphibians, mammals, and arthropods are considered low to very low. An estimated 20 species of herpetofauna were observed such as the Common Forest frog, Cane toad, and Woodworth’s frog. Reptiles such as the rat snake, box turtles, and flying lizards were also noted in the area. Furthermore, a limited number of volant and non-volant mammalian species were also surveyed, most of which are the common short-nosed bats and musky fruit bats. Sighting of the endemic Philippine pygmy bat was also noted, albeit very limited. This kind of bat resides in primary and secondary forests, while the more common ones are normally found in agricultural zones. Aside from the volant mammals, there are also significant records of non-volant mammals such as the native Pinatubo volcano rat, Lowland striped rat, and the Oriental house rat, the latter being considered as pests.

Table 10

Fauna Composition and Diversity within PCRW (CENRO-Dinalupihan, 2021)

Fauna	Count	Example of Species	Shannon Index of Diversity	Interpretation
Avifauna	59 species (21 are endemic)	Philippine Bulbul, Yellow-vented Bulbul, Jungle Nightjar, Himalayan Cuckoo	2.975	High Diversity
Herpetofauna	20 species	Common forest frog, cane toad, flying and monitor lizards, rat snakes, box turtles	1.452	Very Low Diversity
Mammals (volant and non-volant)	17 species	Common short-nosed fruit bat, Philippine pygmy fruit bat, Pinatubo volcano rat	1.596	Very Low Diversity
Arthropods	19 families	Sawflies, wasps, bees, ants, grasshoppers, locusts, crickets, moths, butterflies, bugs, flies, katydids, beetles, termites	2.396	Low Diversity

Finally, a fair number of arthropod species are observed in the watershed, including sawflies, wasps, bees, ants, grasshoppers, locusts, crickets, moths, butterflies, bugs, flies, katydids, beetles, and termites. However, the overall arthropod diversity within PCRW is considered low (CENRO-Dinalupihan, 2021).

Socioeconomic Attributes

Proposed as one of the critical watersheds supporting national irrigation systems (Ejercito, 2016), the PCRW supports agriculture in these provinces by supplying irrigation water for the numerous farmlands in the area. Aside from irrigation water, the watershed also provides several viable potable water sources in the area. For instance, the Stalin Spring in Barangay Roosevelt, Dinalupihan (Figure 2) is utilized as a potable water source by various entities, most notably by the Dinalupihan Water District (DWD), Roosevelt Upland Farmers Association, Inc. (RUFAI), and Roosevelt Water Sanitation and Service Cooperative (RWSSC) (CENRO-Dinalupihan, 2021).

The benefits derived from the watershed have undoubtedly contributed to the significant growth and development of the municipalities in the past decades due to agriculture and urbanization. Naturally, this also entails growth in the population within the watershed. CENRO – Dinalupihan conducted survey and registration of Protected Area occupants (SRPAO) for PCRW in 2021. Results of the study showed that there are 9,745 people in 2,109 households residing within the RPL, while 4,460 people in 1,387 households are registered within the BNP. Moreover, it was found that the majority of these residents living within the watershed belong to the low-income category, with an annual income of Php 250,000 and below. They mostly belong to the blue-collar workforce as construction workers, mechanics, machine operators, factory workers, PUV drivers, service crew, vendors, and delivery riders.

About 3,743 Ha of land on the northern portion of PCRW is classified as ancestral domain (National Commission on Indigenous Peoples, 2015). This area belongs to the Floridablanca Ayta Ancestral Domain, a parcel of land spanning a total of 5,457.71 Ha which was awarded to the Ayta Mag-Indi Community under Certificate of Ancestral Domain Title (CADT) No. RO3-FLO-1206-057-A. This domain covers portions of the municipalities of Floridablanca in Pampanga, and Subic and San Marcelino in Zambales (Floridablanca MPDO, 2016). The Ayta community is centered at the Nabuclod Upland Resettlement Center (NURC) in Floridablanca, one of the established permanent resettlement sites for IPs after the Pinatubo eruption in 1991, although the NURC center is situated outside of the boundaries of PCRW. Historically, Aytas are nomadic hunter and gatherer communities who heavily rely on the natural resources from forests within the watershed, however, the Aytas from NURC nowadays have also learned to rely on vegetable farming through the support of the LGU (Dizon, 1986; Floridablanca MPDO, 2016). Hence, the Aytas from NURC generally have a more secure livelihood through gathering, hunting, farming, and other programs introduced by both local and national government.

RUSLE variables

The variables used for the RUSLE model include rainfall erosivity (R), soil erodibility (K), slope length and steepness (LS), support practice (P), and cover management (C).

Rainfall Erosivity Factor (R)

Being a tropical country, the impact of rainfall and runoff significantly affects the degree of erosion in an area (Ghosal & Das Bhattacharya, 2020). Based on PAGASA (n.d.) and NASA (n.d.) data, the average annual rainfall within PCRW is 3,030.8 mm, with a range of 2,824.2 mm – 3,332.0 mm of rainfall. The highest rainfall was historically recorded on the mountainous southwestern side of PCRW, while the least rainfall was recorded on the northeastern part of the watershed (Figure 6A).

Following equation (1), the computed R factor for the whole PCRW has values ranging from 1,027.0 to 1,204.7 MJ mm/ha h yr, and an average of 1,099.3 MJ mm/ha h yr. The trend for R factor follows that of the rainfall, with lowest and highest values recorded on the northeast and southwest ends of PCRW, respectively (Figure 6B). Areas with higher R factor will likely be more affected by the erosive power of rainfall and runoff.

Soil Erodibility Factor (K)

The K factor directly reflects the contribution of soil type and geology to the susceptibility of the area to erosion. Generally, areas with silt- to clay-rich, organic matter -depleted, and less permeable soils have higher K factor and are more erodible (Ghosal & Das Bhattacharya, 2020). The computed K factor (in t ha h/ha MJ mm) for PCRW ranges from 0.14 to 0.60, with a mean value of 0.3. Higher recorded K factor values correspond to the silty loam to clay-rich soils on the footslopes of Zambales Range and Mt. Natib. Furthermore, the larger percentage of fine sediments and limited organic content in the soils indicate lower permeability. Hence, surface runoff is more pronounced than percolation, leading to a higher rate of soil erosion.

The geology of PCRW is generally volcanic in origin, chiefly due to the proximity of the area to several volcanic centers such as Mt. Natib and Mt. Mariveles, as well as Mt. Pinatubo. As volcanic and pyroclastic rocks are deposited along the slopes of the volcanoes due to repeated episodes of volcanic eruptions over long periods of time, these materials are eventually eroded, broken down, and transported mainly by water. Continuous erosion and weathering of these rocks by water allows for the formation and deposition of abundant clay-rich particles onto the footslopes, and their geologically young age denotes limited accumulation of organic content. Figures 7A and 7B present the soil series map and corresponding K factor Map for PCRW, respectively.

Figure 6. (A) Annual Rainfall Map and (B) corresponding Rainfall Erosivity Factor (R) Map of PCRW.

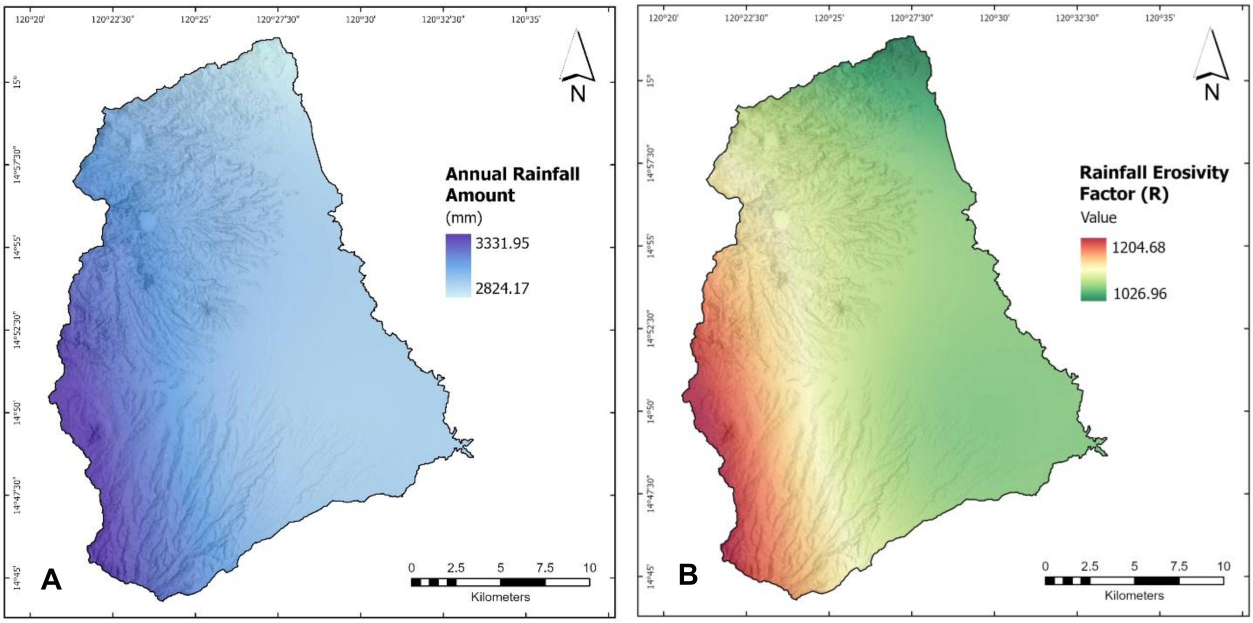


Figure 7. (A) Soil Series Map based on BSWM data and (B) corresponding Soil Erodibility Factor (K) Map of PCRW.

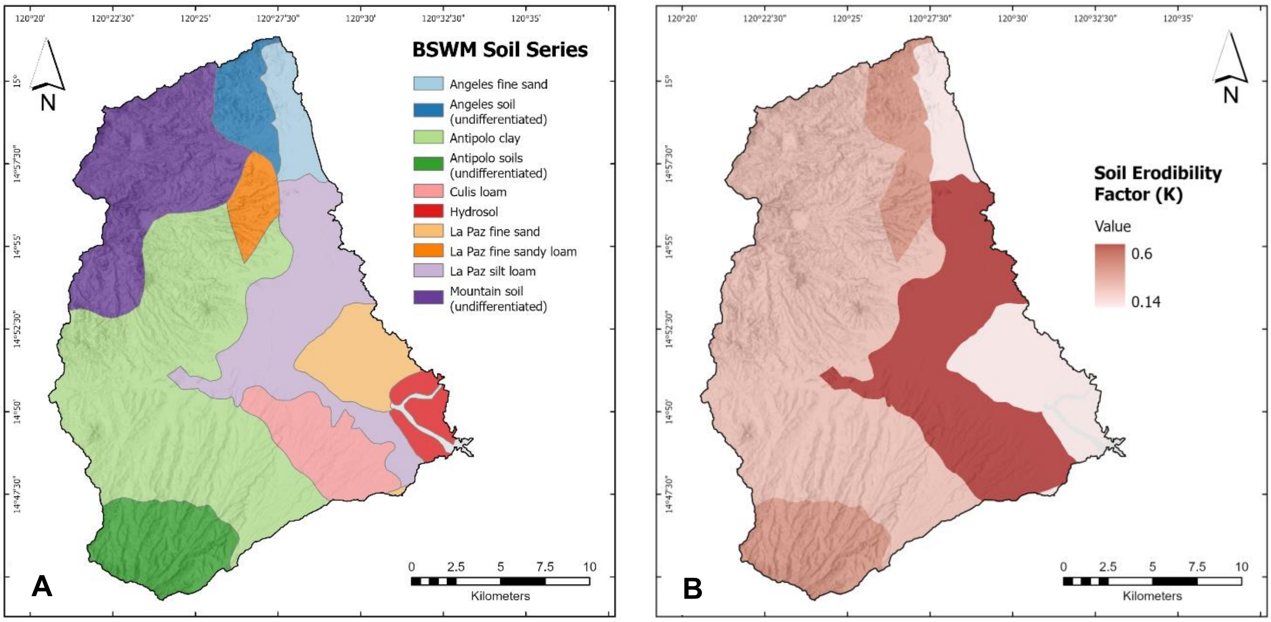
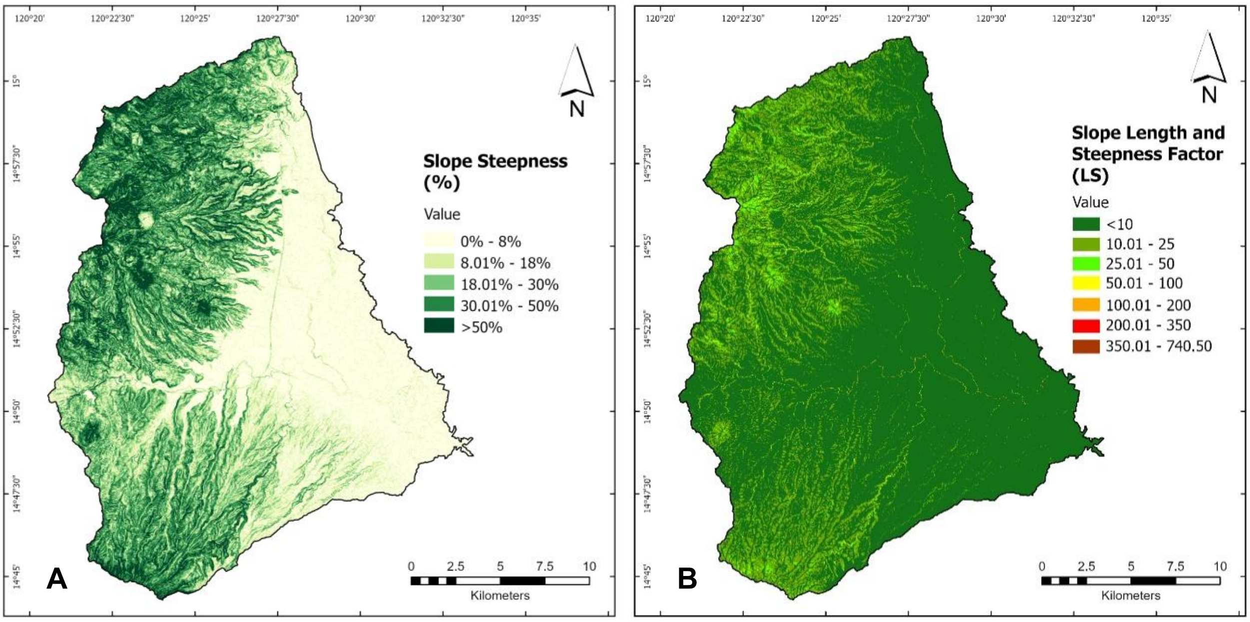


Figure 8. (A) Slope Map and (B) corresponding LS Factor Map of PCRW.



Slope Length and Steepness Factor (LS)

The LS factor relates the effect of the topography, specifically its slope length and steepness, to the degree of erosion in an area. Areas with longer and steeper slopes generally have higher LS factor. Longer slopes allow for greater accumulation of surface runoff while steeper slopes generate faster and more powerful flow. When combined, higher LS factors denote higher overall erosion susceptibility (Ghosal & Das Bhattacharya, 2020).

The computed LS factors for PCRW have a wide range of 0 to 740.5, with an average of 6.2. Expectedly, flat terrain on the lowlands and downstream part of PCRW have lower LS factors due to shorter and gentler slopes. In contrast, the uplands and mountainous terrain on the western part of the watershed generally have steeper and longer slopes, hence the higher LS values. Furthermore, higher LS factors can be generally observed along riverbanks and channels, even on the relatively flatter terrain of the watershed. These higher to even extreme LS values along rivers can indicate localized gradient change possibly due to a meander or knickpoint in the river channel. These can also represent steep riverbank slopes that have been formed either through natural or anthropogenic processes. Figures 8A and 8B present the slope map and corresponding LS factor Map for PCRW, respectively.

Cover Management Factor (C)

The C factor relates how land use and soil cover contribute to soil erosion in an area. Generally, areas with substantial soil cover such as forestlands or the impervious surfaces of urban areas have low C-factor scores as the cover they provide limits the erosive impact of runoff and rainfall to the soil. Consequently, areas with limited vegetation such as agricultural lands and barren lands have C factor scores close to 1. Analysis of changes in land use / cover over time helps in determining patterns and dynamics of land use conversion and their implications to soil erosion risk (Ghosal & Das Bhattacharya, 2020).

Land Use / Land Cover (LULC) Change Analysis. In 2014, forestlands occupy most of the watershed with 14,267 Ha or 33.9% of the total land area. This was followed by agricultural lands at 21.0%, grasslands and shrublands at 20.4%, barren lands at 18.6%, built-up areas at 3.7%, and water bodies at 2.4%. By 2024, forest cover was reduced to only 18.8% of the total land area of the watershed, while agricultural lands jumped to 39.5%. Urban areas slightly increased to 4.4%.

Within a span of 10 years from 2014 to 2024, a major drop in net forest cover of about 45% was recorded in PCRW based on LULC change analysis. The sharp decrease was especially recorded from 2014 to 2017, then followed by minor increase in forest cover from 2017 to 2024. Forest cover on the flanks, footslopes, and backslopes of Zambales Range and partly of Mt. Natib, both on the western part of the watershed had been significantly reduced, leaving only the core forest part mostly situated on the 400-m elevation and above.

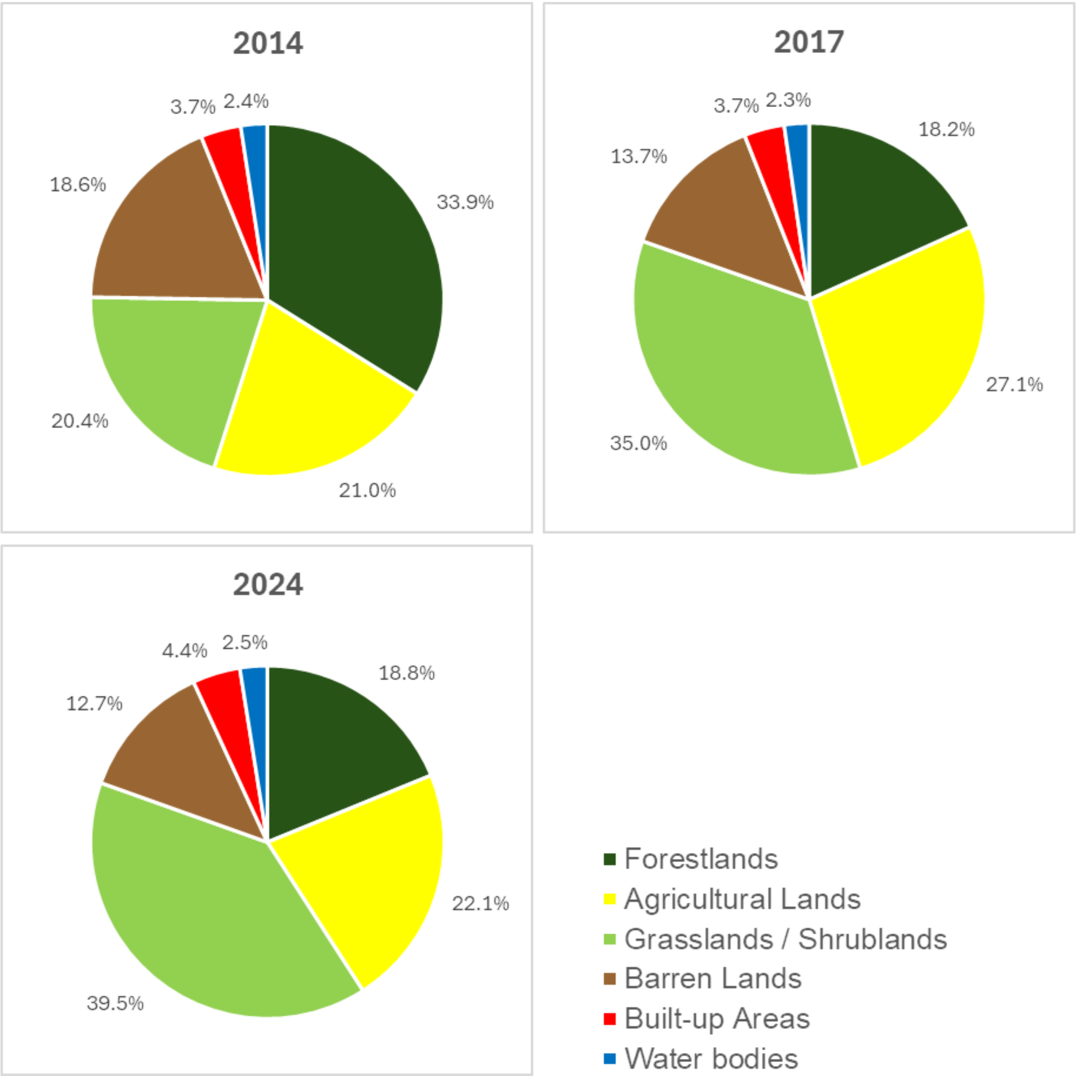
Barren lands had also decreased between 2014 and 2024 by as much as 32% of its original cover in 2014. Some of the barren lands on the flanks of Mt. Natib south of PCRW have been converted mostly to grasslands or shrublands. On the other hand, a substantial area on the higher elevations north of the watershed have been converted to barren lands from being shrublands.

A significant area of former forestlands and barren lands on the higher elevation areas and steep flanks of PCRW have been converted to grasslands or shrublands, accounting for a net 94% increase in area covered from 2014. Moreover, the lowlands had seen a proliferation of patches of grasslands and shrubs embedded in a matrix of agricultural lands.

Built-up areas have also increased in coverage by 18% between 2014 and 2024. Aside from the densification of existing communities on the lowlands especially those along major highways, there has also been a marked spike in patches of built-up areas along the footslopes and valleys of Mt. Natib and Zambales Range.

Minimal net positive changes in area covered were recorded for agricultural lands and water bodies. For the former, a total net increase by 5% was noted between 2014 and 2024, where slight increase from 2014 to 2017 was attributable to the conversion of grasslands and barren lands on the footslopes of the mountains into farmlands. However, there was a minor drop in agricultural cover between 2017 and 2024 mainly due to the increase of grassland patches on the lowland area east of the watershed.

Figure 9. Percent distribution of land use / land cover within PCRW for years 2014, 2017, and 2024.



Finally, water bodies generally had minimal movement in terms of area, and these represent inland water bodies such as rivers and ponds, as well as estuaries, fishponds, and major rivers on the southeastern end of the watershed leading to Manila Bay.

Figure 9 presents the distribution of land cover within the PCRW, while Figure 10 and Table 12 summarize the area change per land cover for years 2014, 2017, and 2024. Finally, Figures 11A-E show the actual LULC Maps of PCRW for 2014, 2017, and 2024.

To assess the accuracy of the Land Use / Land Cover Classification, a confusion matrix was prepared and the corresponding Kappa coefficients for the three time periods were computed. Results showed 0.894, 0.862, and 0.827 Kappa statistics for years 2014, 2017, and 2024, respectively. Based on this statistic, results of LULC classification have good, acceptable accuracy and agreement between classified and reference values (Table 11).

Figure 10. Comparison of change in area covered per land use classification in PCRW for years 2014, 2017, and 2024*.*

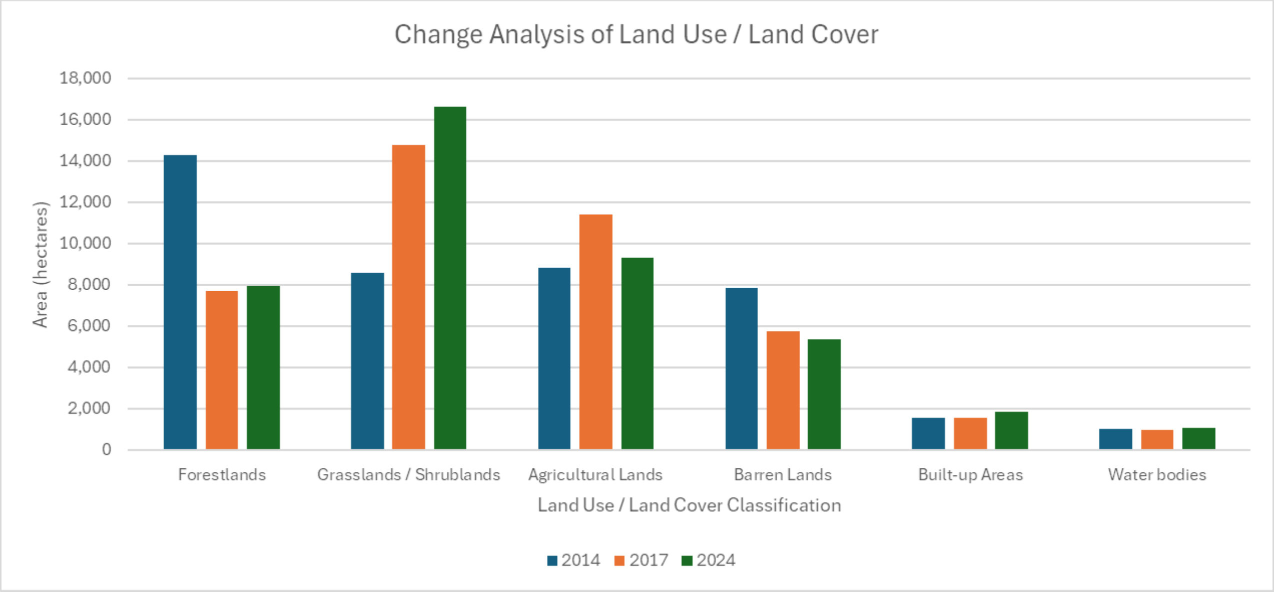


Table 11

Accuracy Assessment using Kappa Coefficient for Land Use Classification in PCRW for years 2014, 2017, and 2024

Year	Overall Accuracy	Kappa Coefficient
2014	91.4%	0.894
2017	88.6%	0.862
2024	85.7%	0.827

Table 12

Summary of Area covered per Land Use Classification in PCRW for years 2014, 2017, and 2024

Land Cover / Land Use Classification	Area Covered (hectares)			10-year net change
	2014	2017	2024	
Forestlands	14,267	7,689	7,916	-44.5%
Grasslands / Shrublands	8,574	14,766	16,640	94.1%
Agricultural Lands	8,834	11,424	9,304	5.3%
Barren Lands	7,842	5,755	5,333	-32.0%
Built-up Areas	1,551	1,554	1,835	18.3%
Water bodies	1,015	959	1,054	3.8%

Generated C factor layers. Following the results of the land use classification, C factor classification for the three time periods show low values for the water bodies and built-up areas in the low-lying eastern part of the watershed as well as the forestlands on the higher altitude portions. Moreover, areas classified as farmlands and grasslands which are partially covered by vegetation have C values between 0-1. Finally, barren lands with little to no vegetative cover have high C values (Figure 12).

Conservation or Support Practice Factor (P)

The P factor represents the effect of the presence or absence of soil conservation and land management practices in reducing soil erosion occurrence, where P factor values closer to 1 indicate effective conservation practices (Ghosal & Das Bhattacharya, 2020). In the case of PCRW, data on conservation practices employed are insufficient and incomplete, hence, P factor calculation was derived from existing land cover and slope steepness, following the works of Yigez et al. (2021).

Figure 11. Comparison of satellite imagery (A, C, E) and classified imagery (B, D, F) of PCRW for the years 2014, 2017, and 2024

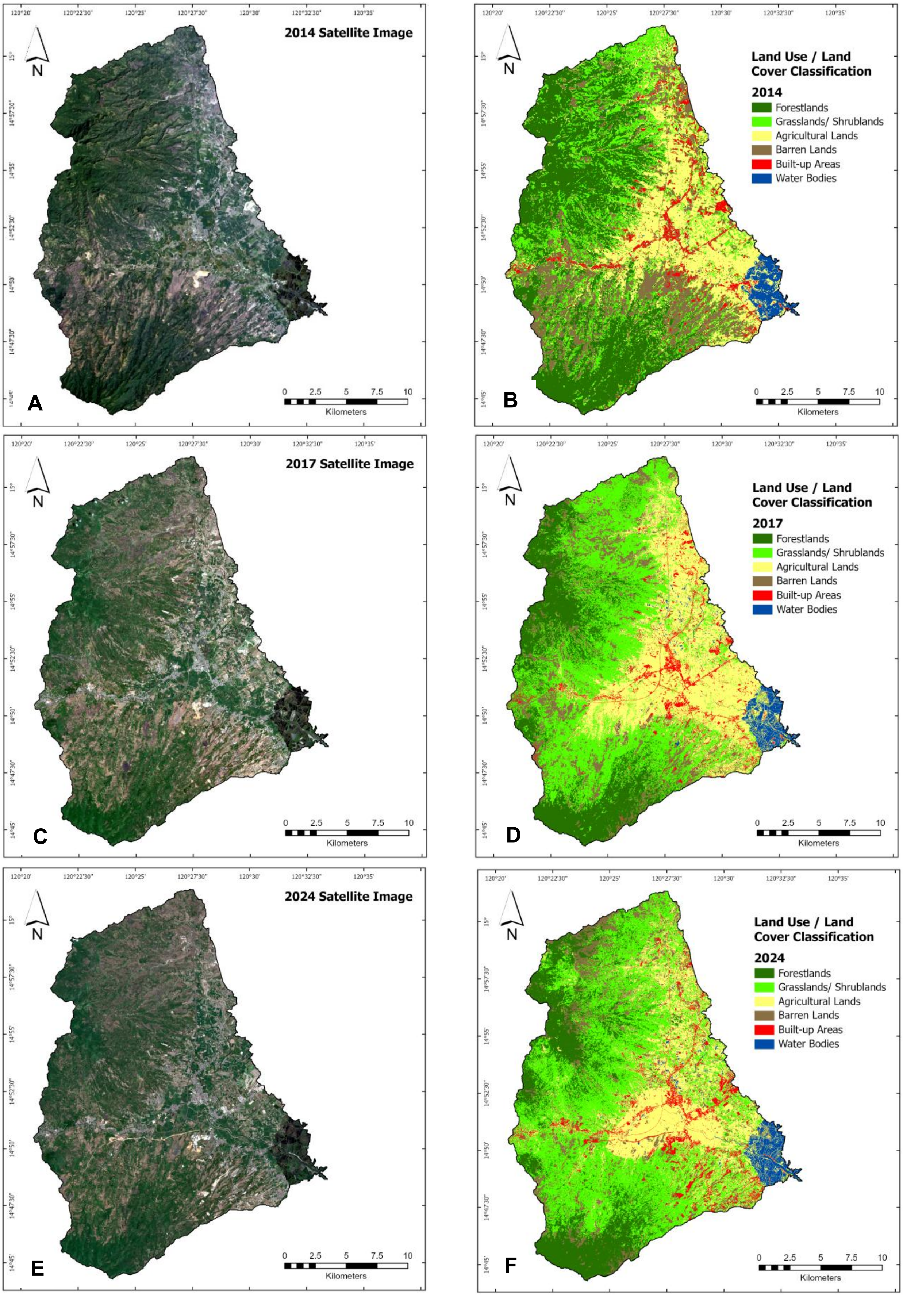
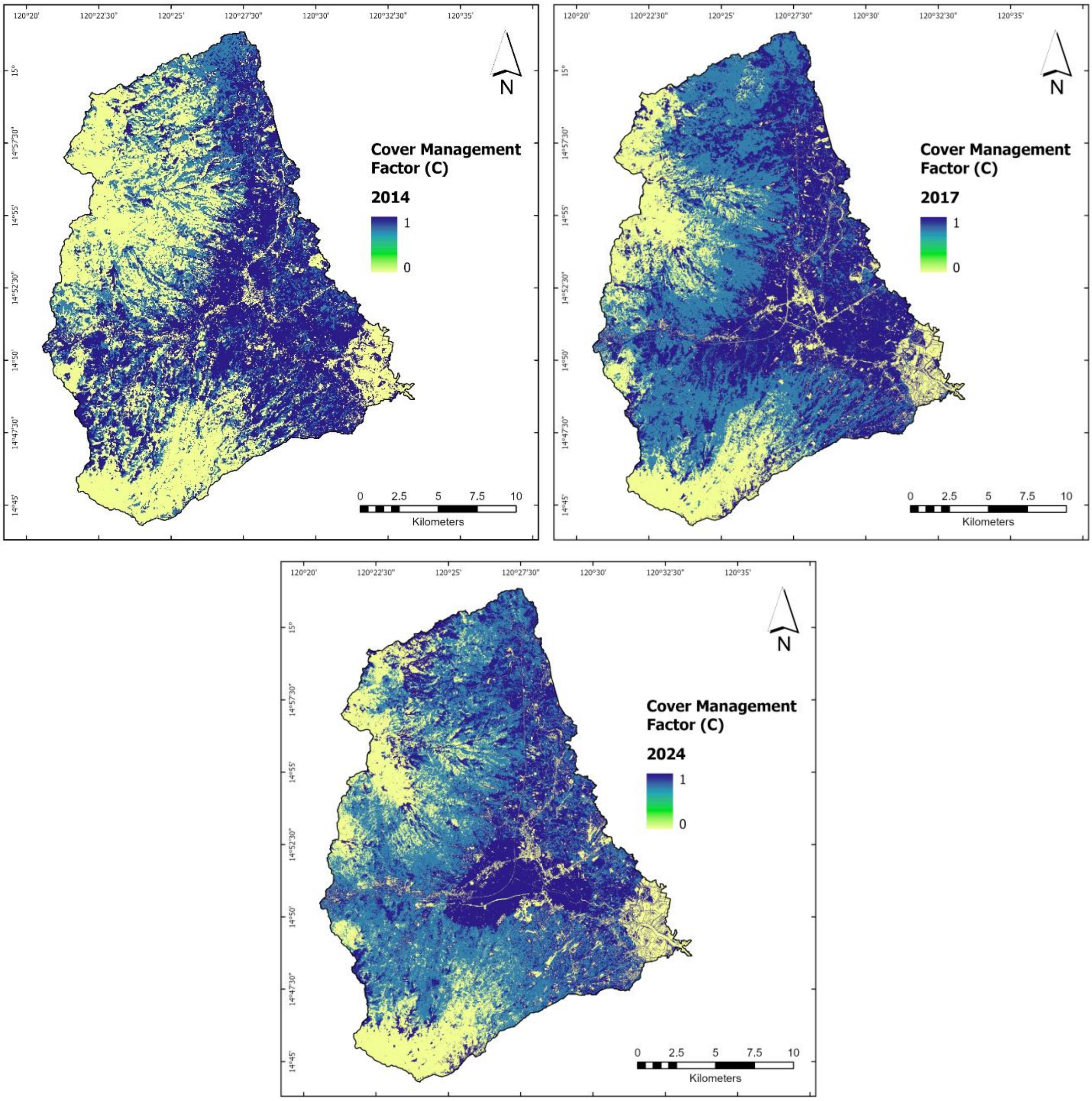
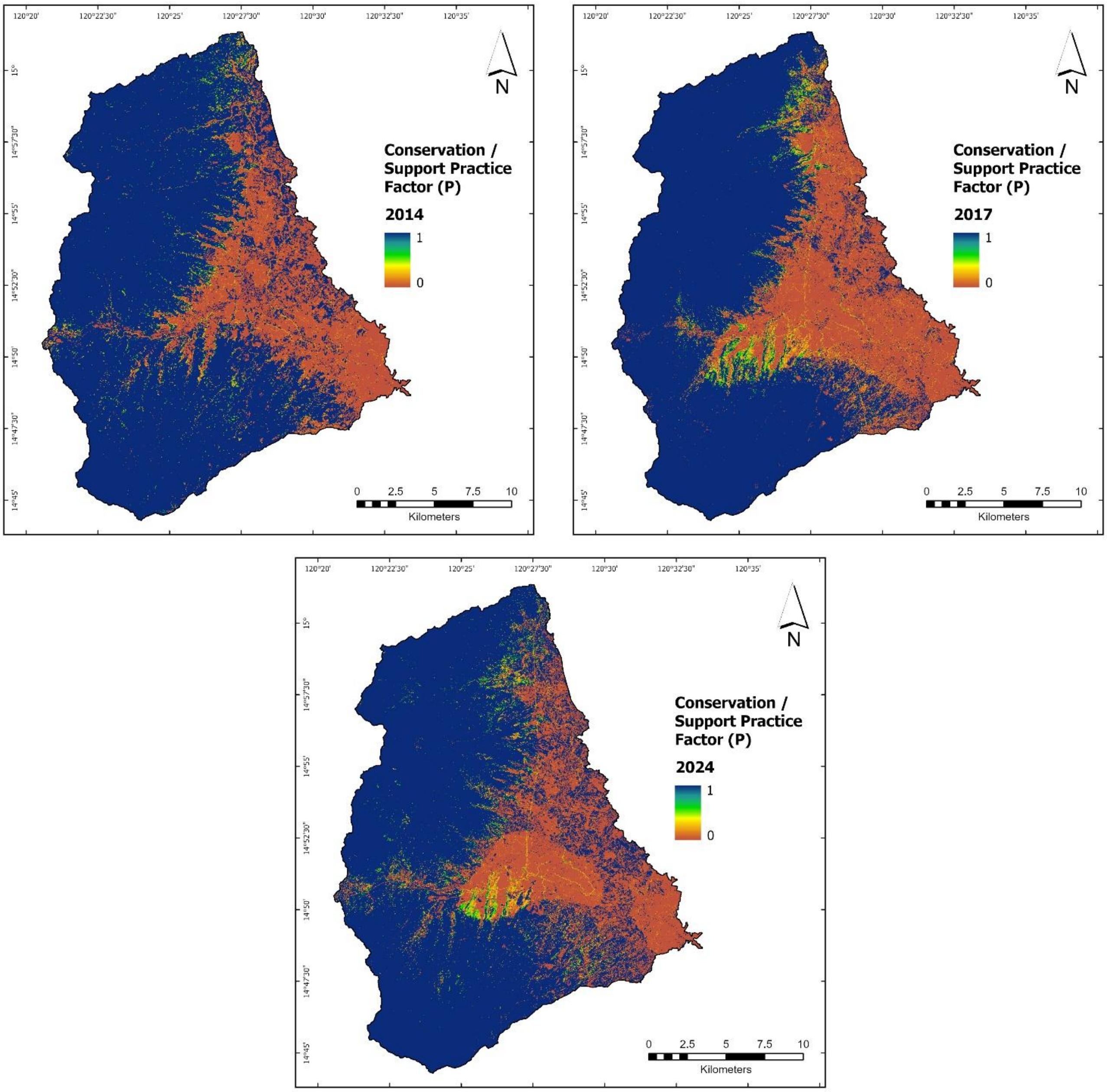


Figure 12. Cover Management Factor (C) Maps of PCRW for the periods 2014, 2017, and 2024.



Using said factors, natural land cover classifications such as forests, grasslands, and barren lands without artificial conservation measures are assigned with P factor of 1, since these areas have conservation measures implemented at a natural level (e.g. natural vegetation and topography). Meanwhile, agricultural areas, where human interventions are typical, have P values between 0 and 1 depending on the slope steepness in the area. Finally, built-up areas and water bodies where these practices are not applicable have P factor scores of 0 (Wischmeier & Smith, 1978).

Figure 13. Conservation / Support Practice Factor (P) Map of PCRW for the periods 2014, 2017, and 2024.



Results showed that the majority of the lowlands on the eastern side of the watershed are composed of low-gradient agricultural lands and built-up areas. Hence, P factor values here are generally lower. Towards the west where slopes become steeper and land cover transitions into natural vegetation, P factor values are pegged at 1. Generally, average P factor values from 2014, 2017, and 2024 range from 0.70 to 0.75.

Since the P factor values for this study relied on land cover classification, three P factor maps were prepared representing years 2014, 2017, and 2024. These are presented in Figure 13.

RUSLE Model and Soil Erosion Risk Assessment

Figure 14 presents the soil erosion risk maps of the PCRW for the years 2014, 2017 and 2024 prepared using GIS techniques and the RUSLE model.

Table 13

Summary of Statistics for the Computed Soil Loss Rates in PCRW for years 2014, 2017, and 2024

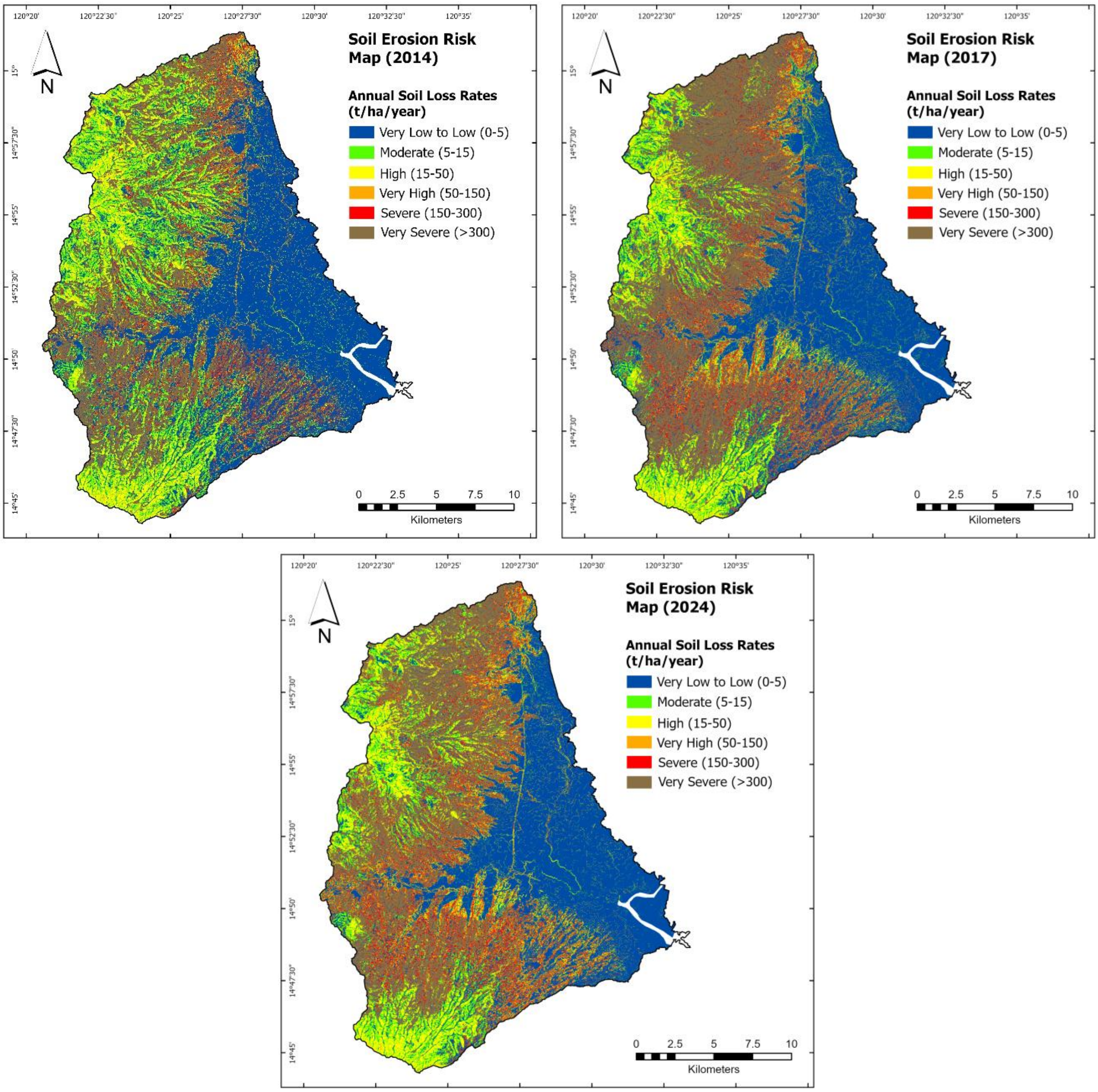
Year	Soil Loss Rates (t/ha/year)		
	Minimum	Maximum	Mean
2014	0	40,617	285
2017	0	40,619	417
2024	0	34,475	352

Table 14

Summary of Area covered per Soil Erosion Risk Category in PCRW for years 2014, 2017, and 2024

Annual Soil Loss (t/ha/yr)	Risk Category	2014		2017		2024	
		Area (Ha)	Percent	Area (Ha)	Percent	Area (Ha)	Percent
0-5	Very Low to Low	18,445.9	44.1%	16,956.1	40.5%	16,283.0	38.9%
5-15	Moderate	6,397.4	15.3%	3,835.8	9.2%	3,981.2	9.5%
15-50	High	4,788.4	11.5%	3,892.1	9.3%	4,304.9	10.3%
50-150	Very High	1,583.8	3.8%	2,061.4	4.9%	2,563.5	6.1%
150-300	Severe	1,930.6	4.6%	2,573.2	6.1%	3,008.7	7.2%
>300	Very Severe	8,655.4	20.7%	12,551.5	30.0%	11,696.2	28.0%

Figure 14. Soil Erosion Risk Maps of PCRW for years 2014, 2017, and 2024.



Results show that the average annual soil erosion in PCRW from 2014, 2017, and 2024 can be categorized as severe to very severe (Table 13). The study also identified a significant soil erosion risk in the PCRW (Figure 15), with 29% to 41% of the whole study area categorized as having very high to very severe erosion risk from

2014, 2017, and 2024, respectively (Table 14). In particular, areas categorized under very severe risk, or those with annual soil loss rate of more than 300 t/ha/year, covers 20% of total land area in 2014 which then jumped to 30% in 2024. These areas are concentrated primarily on the middle elevations, the steep footslopes and backslopes of Mt. Natib and Zambales Range.

Areas with moderate to high soil erosion risk, or those with annual soil loss rate of 5 – 50 t/ha/year, are mostly concentrated on the upper elevations and around the peaks of the mountain ranges west and south of the watershed. These areas comprise 27% of the total area in 2014. However, a decline to 19% was noted in 2024. Moreover, low-lying areas with generally level to gentle slopes east of the watershed have the least risk to soil erosion. These areas with very low to low erosion risk also occupy majority of PCRW but showed slight decline during the 10-year span, from 44% in 2014 to 39% in 2024.

In terms of the relationship of land use / land cover and soil erosion risk, majority of areas with very high to very severe soil erosion risk rating are sparsely vegetated zones such as barren lands and grasslands / shrublands. Moreover, there is a recorded drastic increase in grasslands/shrublands identified under this erosion risk category, from about 4,280 Ha in 2014 to 7,895 Ha in 2024. This land use class represents majority of all areas under severe to very severe erosion risk, followed by barren lands.

Areas with relatively dense secondary forests on the upper elevations are under moderate to high soil erosion risk. A total of 9,923 Ha of forestlands were classified under moderate to high risk in 2014, marking more than 80% of all areas under this risk category. However, a general decline in areas under this category was noted for 2024 as only about 5,714 Ha of forestlands remained under moderate to high erosion risk.

Finally, land cover types occupying the low-lying areas such as agricultural lands, built-up areas, grasslands, and some barren lands, as well as upland forests on relatively gentle slopes are categorized under very low to low erosion risk. In 2014, the majority of low erosion risk zones were occupied by forestlands and agricultural lands. However, by 2024, it was evident that land cover shift from forests to grasslands / shrublands and agricultural areas has led to the prevalence of the latter in low-risk zones. Likewise, built-up areas such as residential, industrial, and major roads are mostly situated in low erosion risk zones, except for several patches of urban areas in the towns of Dinalupihan, Hermosa, and Orani which are situated on the footslopes of Mt. Natib and Zambales Range with high to very severe erosion risk.

The summary of the relationship between land cover / land use and soil erosion risk from 2014, 2017, and 2024 is presented in Tables 15-17 and Figures 16-18.

Table 15

Summary of Soil Erosion Risk per Land Use Classification for year 2014

Land Cover Classification	**Area Covered (in hectares)**											
	Very Low to Low		**Moderate**		**High**		**Very High**		**Severe**		**Very Severe**	
Water Bodies	864.4	4.7%	0.0	0.0%	0.0	0.0%	0.0	0.0%	0.0	0.0%	0.0	0.0%
Built-up Areas	1,528.2	8.3%	0.0	0.0%	0.0	0.0%	0.0	0.0%	0.0	0.0%	0.0	0.0%
Barren Lands	3,006.0	16.3%	0.0	0.0%	6.6	0.1%	184.6	11.7%	525.4	27.2%	4,108.1	47.5%
Agricultural Lands	6,521.1	35.4%	388.6	6.1%	708.7	14.8%	568.6	35.9%	297.3	15.4%	267.5	3.1%
Grasslands / Shrublands	2,272.7	12.3%	6.3	0.1%	152.8	3.2%	747.7	47.2%	1,107.6	57.4%	4,279.8	49.4%
Forestlands	4,253.5	23.1%	6,002.5	93.8%	3,920.4	81.9%	82.9	5.2%	0.2	0.0%	0.0	0.0%

Table 16

Summary of Soil Erosion Risk per Land Use Classification for year 2017

Land Cover Classification	Area Covered (in hectares)											
	Very Low to Low		Moderate		High		Very High		Severe		Very Severe	
Water Bodies	810.4	4.8%	1.6	0.0%	1.2	0.0%	0.5	0.0%	0.2	0.0%	0.4	0.0%
Built-up Areas	1,507.5	8.9%	4.2	0.1%	8.0	0.2%	5.8	0.3%	4.2	0.2%	13.2	0.1%
Barren Lands	1,523.9	9.0%	22.1	0.6%	53.5	1.4%	160.9	7.8%	339.1	13.2%	3,643.3	29.0%
Agricultural Lands	8,579.3	50.6%	566.2	14.8%	953.8	24.5%	647.2	31.4%	286.2	11.1%	304.6	2.4%
Grasslands / Shrublands	2,807.3	16.6%	152.1	4.0%	315.9	8.1%	1,168.8	56.7%	1,911.8	74.3%	8,393.1	66.9%
Forestlands	1,727.6	10.2%	3,089.6	80.5%	2,559.7	65.8%	78.1	3.8%	31.6	1.2%	197.0	1.6%

Table 17

Summary of Soil Erosion Risk per Land Use Classification for year 2024

Land Cover Classification	Area Covered (in hectares)											
	Very Low to Low		Moderate		High		Very High		Severe		Very Severe	
Water Bodies	902.0	5.5%	2.6	0.1%	2.6	0.1%	1.6	0.1%	0.4	0.0%	0.3	0.0%
Built-up Areas	1,746.4	10.7%	15.1	0.4%	26.1	0.6%	16.8	0.7%	7.9	0.3%	13.9	0.1%
Barren Lands	1,880.0	11.5%	82.7	2.1%	128.2	3.0%	204.6	8.0%	289.0	9.6%	2,738.1	23.4%
Agricultural Lands	6,523.8	40.1%	417.2	10.5%	802.2	18.6%	691.0	27.0%	356.3	11.8%	448.2	3.8%
Grasslands / Shrublands	3,859.5	23.7%	440.2	11.1%	655.3	15.2%	1,542.1	60.2%	2,237.4	74.4%	7,894.8	67.5%
Forestlands	1,371.4	8.4%	3,023.4	75.9%	2,690.5	62.5%	107.4	4.2%	117.9	3.9%	601.0	5.1%

Figure 16. Distribution of Soil Erosion Risk per Land Use Classification for year 2014.

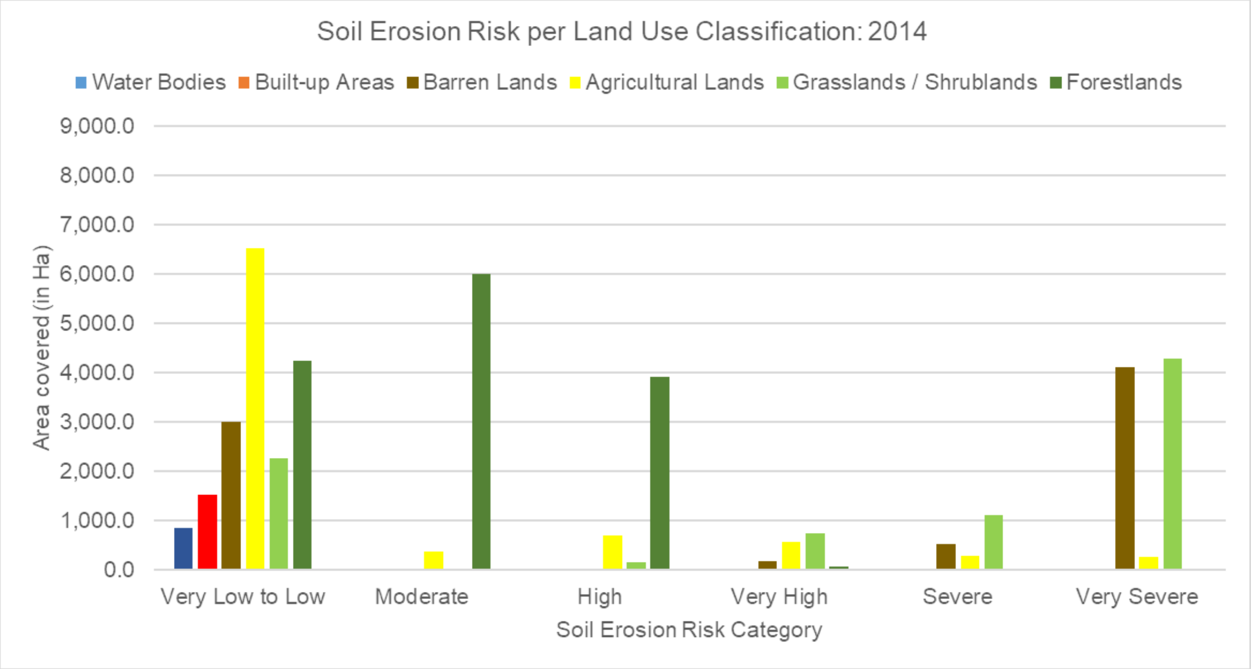


Figure 17. Distribution of Soil Erosion Risk per Land Use Classification for year 2017.

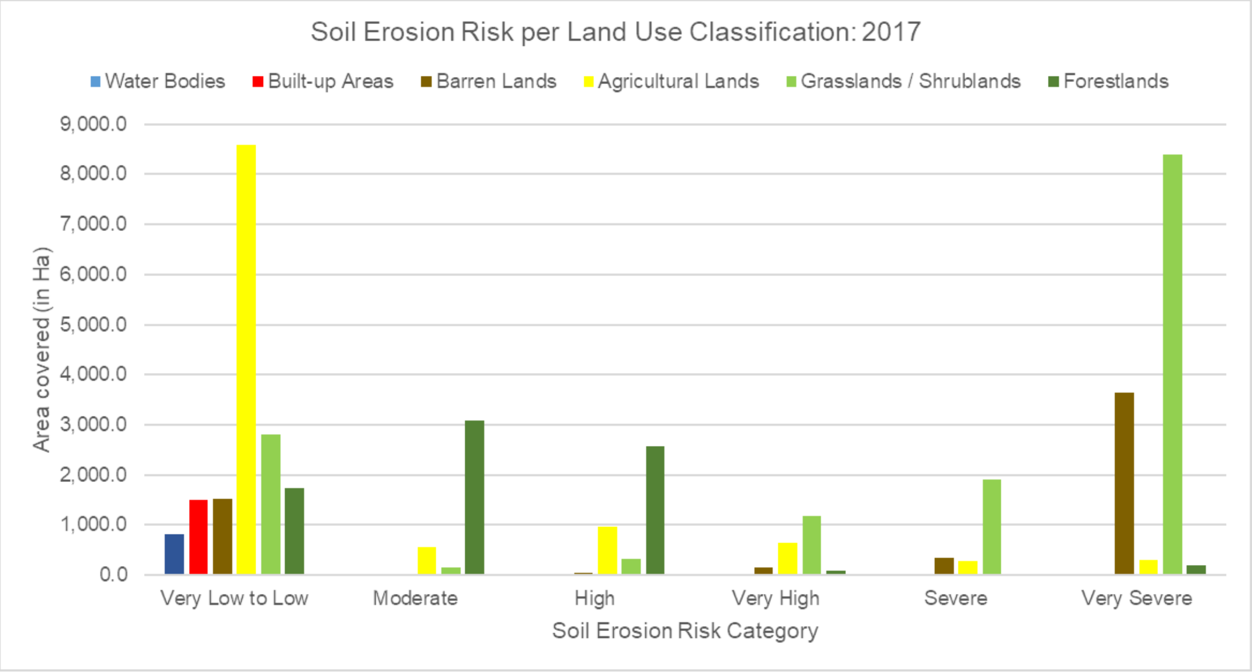
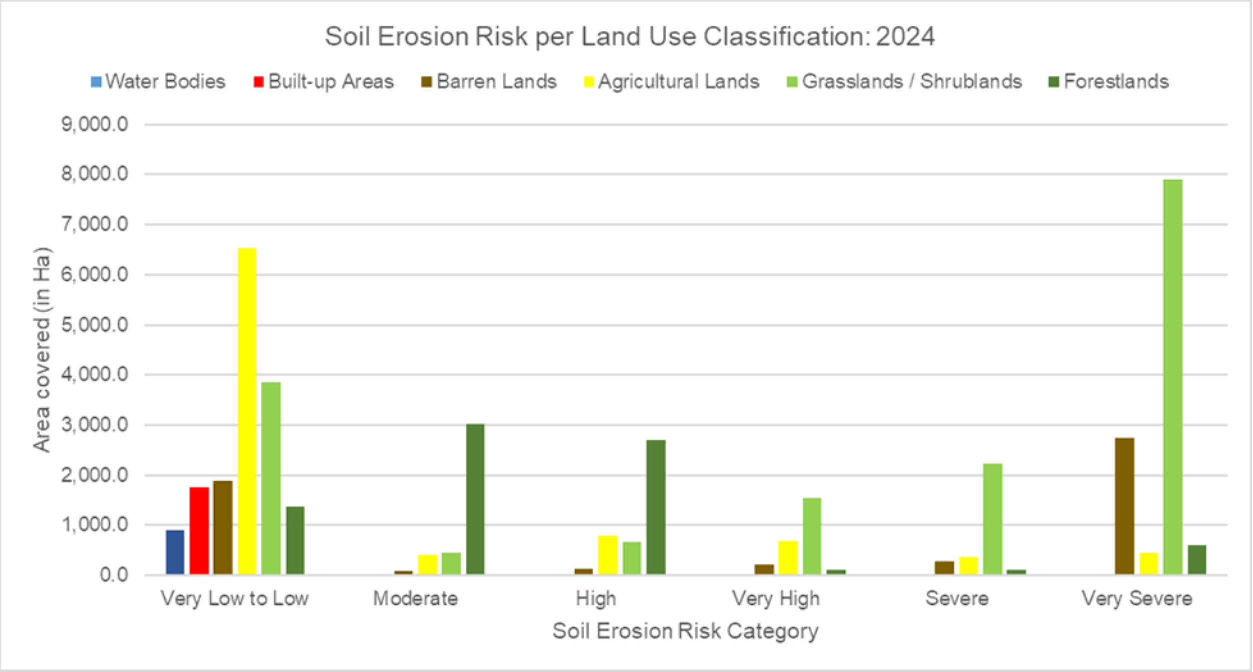


Figure 18. Distribution of Soil Erosion Risk per Land Use Classification for year 2024.



Watershed Conservation and Management

Watershed and Protected Areas Management Plans

Managing and preserving the PCRW and the PAs within it falls under the responsibility of various agencies and concerned LGUs. Primarily, the Department of Environment and Natural Resources through their Provincial Offices in Pampanga, Bataan, and Zambales oversee the management of PCRW. Specifically, the CENRO – Dinalupihan in Bataan shoulders one of the main responsibilities since majority of the total area of PCRW falls within its jurisdiction. In relation to this, the proposed Integrated Watershed Management Plan (IWMP) for the PCRW has been formulated in 2021 and its approval and legitimization is underway. The IWMP is a collaborative effort amongst the DENR and other NGAs, the LGUs concerned, People's Organizations (POs), Non-government Organizations (NGOs), Academe, and concerned communities for the sustainable development of the watershed. Representatives from these agencies and institutions shall later form the Watershed Management Council for PCRW. The IWMP shall employ a holistic, integrated, ridge-to-reef ecosystems approach where the well-being of local communities is also accounted for. Under this IWMP, some of the most important strategies recommended to address the erosion-related environmental problems include the (1) establishment of a multi-sectoral management council to oversee the implementation of management measures as well as regular monitoring of the area, (2) use of assisted natural regeneration of forests through agroforestry and enrichment planting, (3) riverbank stabilization, (4) structural or engineering practices, (5) community knowledge enrichment and involvement, (5) fire management and law enforcement, (6) restoration of silted river systems, (7) allocation of best land uses, and (8) management zones delineation.

The IWMP also details that, in addition to the PCRW as a whole, the protected areas within its uplands are also managed separately by their respective Protected Area Management Board (PAMB) as the central decision-making body by virtue of RA 7586 (National Integrated Protected Areas System Act of 1992). Currently, the PAMB of RPL and BNP oversee the several tenurial instruments awarded to People's Organizations within these protected areas. For the RPL, these include eight existing Memoranda of Agreement (MOA) and Special Use Agreement in Protected Area (SAPA) with total coverage of 2,232 Ha. For the BNP, there are seven existing MOAs and SAPA, with a total area of 568 Ha. Moreover, Community-based Forest Management Agreements (CBFMA) have also been awarded to various POs within the watershed, such as the Pita Upland Farmers Multi-Purpose Cooperative (26.87 Ha), Mt. View Upland Farmers Association (453.43 Ha), and Roosevelt Upland Farmers Association (57.22 Ha) (CENRO-Dinalupihan, 2021).

However, as far as soil erosion assessment and conservation is concerned, the proposed IWMP does not contain detailed soil erosion risk assessment studies. The IWMP also does not elaborate on specific measures in relation to the general management strategies presented above. Moreover, specific GIS-aided research and modelling on key issues such as soil erosion and sedimentation, water balance, and water use are only added as proposed future research studies to be used as supplement to the IWMP.

Aside from the IWMP which covers the watershed as a whole, there are also specific PAs within the PCRW which are also managed by their respective Protected Area Management Offices (PAMO). Among these, the BNP covers the largest portion of PA that is within the boundaries of PCRW, totaling 4,834.14 Ha in the southern portion of PCRW. According to the proposed CY 2021-2030 Protected Area Management Plan (PAMP) of the BNP (Protected Area Management Office - Bataan Natural Park, 2021), it was identified that climate change / global warming is the second highest threat that may affect both the PAs and the watershed as a whole, as this threat can aggravate into more severe climatic and weather events which are outside of the natural range of variations within the watershed. Hence, it is highly important for the management to address the possible impacts of climate change, such as soil erosion, through enhanced mitigation and rehabilitation efforts.

In this regard, one of the main management foci for the BNP is resource protection and monitoring. Under this, activities include regulation of order within the PAs through the assistance of park rangers. Another is the restoration and rehabilitation of degraded habitats through vulnerability assessments, and the implementation of assisted natural regeneration, riverbanks restoration, and the National Greening Program (PAMO-BNP, 2021).

Another focus is the community-based resource management through agreements with different municipalities and stakeholders within the BNP such as the Tabalan MFPC Association, Inc. covering 300 Ha in Hermosa, Bataan. This agreement involves stakeholder partnerships for the holistic management of the awarded sites such as habitat and biodiversity conservation, efficient resource utilization, and development of alternative livelihoods.

However, much like in the proposed IWMP, there are no specific and detailed information on soil erosion management and mitigation within the protected area management plans aside from the generalized recommendations such as the implementation of mitigation measures, conduct of site-specific studies, declaration of “No Habitation / No Build Zones” in landslide prone areas, and regular monitoring for appearance of signs of impending landslides. Moreover, the report also mentions that the sustainable implementation of said conservation and protection measures within the PAs are currently being limited by manpower and funding constrains.

National Greening Program (NGP)

One of the major management measures for the PCRW and the protected areas within it is the National Greening Program (NGP). This program is managed by the DENR in partnership with various LGUs, People's Organizations, Academic Institutions, and Private Sector (CENRO-Dinalupihan, 2021).

Review of data from the CENRO-Dinalupihan (n.d.) on the existing NGP Reforestation sites within PCRW showed that there has been approximately 4,087 Ha of dedicated reforestation sites in the area from 2011 to 2016, approximately 2,380 Ha of which are within the three PAs in the area, namely: RPL, BNP, and OWFR. Most of the NGP sites within the PAs host timber commodities such as Narra and Dungon, as well as some agroforestry products including coffee and cacao. The remaining sites are outside these PAs, spread among production forest zones, dedicated agroforestry sites, CBFMAs sites, riparian areas, and urban corridors. Commodities hosted in these areas include timber stands of Narra, Molave, and Kakawate, fruit-bearing trees such as cashew, guyabano, jackfruit, coffee, and various species of bamboo.

Figures 19-21 present the distribution of land cover and area covered for each soil erosion risk rating within the NGP reforestation sites from 2014, 2017, and 2024. Results show that 2,380 Ha or 58% of the total area of the NGP sites are situated within the PAs, while the rest are located on production forests, slopes of Zambales Range, and riparian areas outside the PAs. A large majority of the NGP sites are categorized under very severe soil erosion risk, especially those situated on the footslopes north of PCRW. Meanwhile, NGP sites within the PAs are mostly under moderate to high erosion risk. Moreover, plantation sites along rivers and urban areas on the lowlands are under very low to low erosion risk. Figure 21 also shows that steeply sloping areas surrounding the PAs on the footslopes and backslopes of Mt. Natib and Zambales Range are under very high to very severe soil erosion risk. Looking at the LULC maps presented in Figure 11, these very severe erosion zones also correspond to areas with sparse vegetation cover (i.e. barren lands, grasslands / shrublands).

It is evident that from 2014 to 2017, there has been an increase in areas within the NGP sites that were categorized under high to very severe erosion risk, while a slight decrease in very severe risk was observed from 2017 to 2024. This translates to 37%, 53%, and 47% of total reforestation sites having very severe erosion risk in 2014, 2017 and 2024, respectively.

Figure 19. Comparison of change in area covered per soil erosion risk category within reforestation sites in PCRW for years 2014, 2017, and 2024.

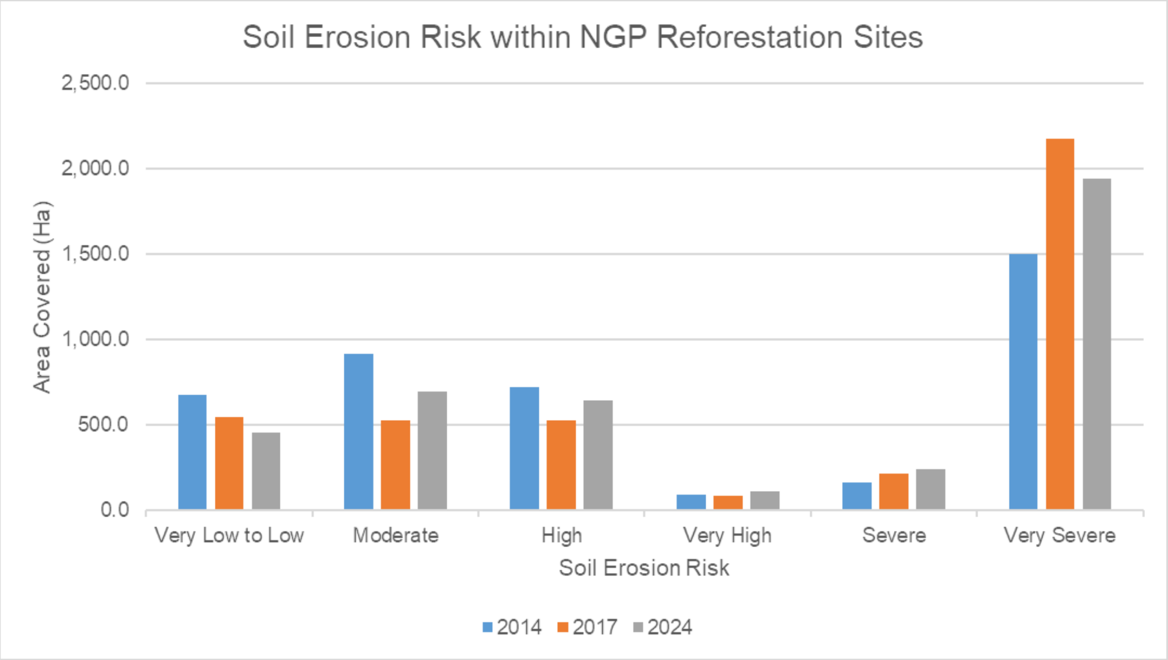
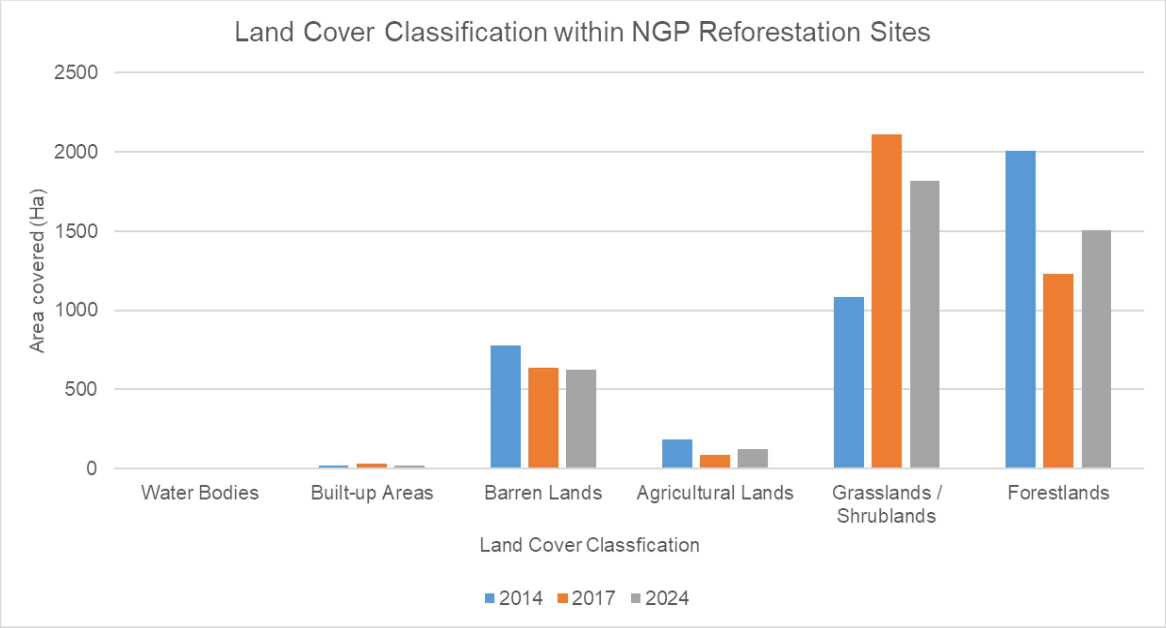


Figure 20. Comparison of change in area covered per land use classification within reforestation sites in PCRW for years 2014, 2017, and 2024.



Local Government Units (LGUs)

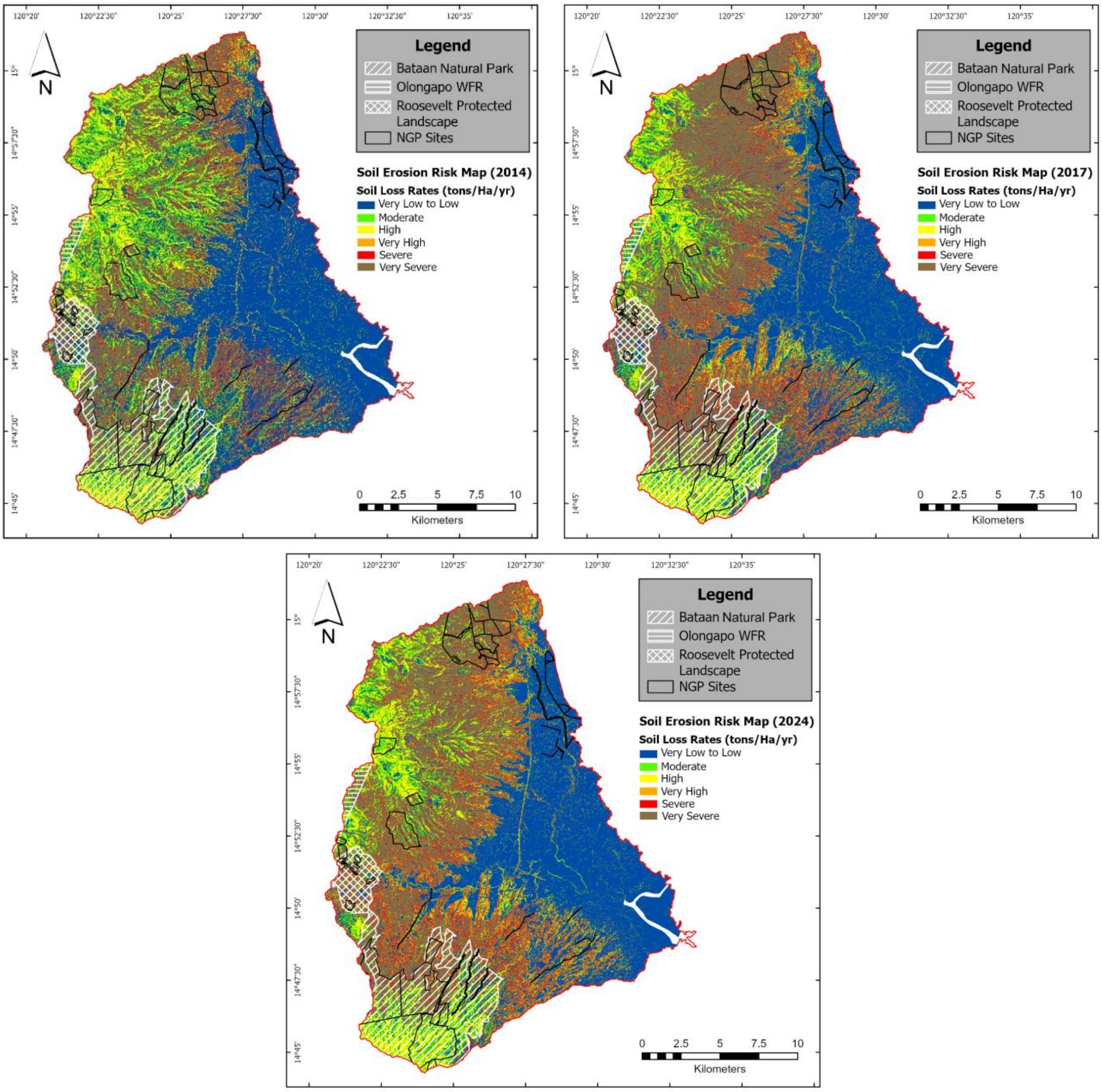
Aside from the NGAs, LGUs also play important roles in the management of watersheds and protected areas. Since the LGUs have more localized reach, they are able to ascertain more specific issues and concerns within the PCRW. These LGUs present identified environmental issues, as well as proposed mitigating measures, in various documents including CLUPs and Municipal Ecological Profiles (Dinalupihan Planning and Development Office, n.d.; Floridablanca Municipal Planning and Development Office, 2016; Orani Municipal Planning and Development Office, 2019). In addition, the Dinalupihan PDO has also adopted its Forest Land Use Plan or FLUP (2019) to properly address environmental issues in the area, including *kaingin* (slash-and-burn farming), timber poaching, boundary disputes, lack of manpower with sufficient management and conservation expertise, conflicts in ancestral domain claims, encroachment of Informal Settler Families (ISFs) into forestlands and PAs, and in the case of Dinalupihan, the lack of a dedicated Municipal Environment and Natural Resources Officer (MENRO) and needed staff.

In relation to these, the LGUs recognize the need to put focus on establishing enough manpower and experts to focus on environmental management, to collaborate with agencies such as the DENR and neighboring LGUs to address concerns that transcend municipal boundaries, to strengthen thrust towards agroforestry development, and to implement urban greening and restoration of public open spaces (Orani MPDO, 2019).

Finally, the management roles for the lowland, urban, and coastal/marine zones of PCRW are also fulfilled by concerned LGUs in the area. Part of their responsibilities is to properly implement the provisions set by various environmental laws such as RA 9003 on ecological solid waste management, Philippine Clean Air Act of 1999, Philippine Clean Water Act of 2004, among other pertinent rules and regulations. Several practices have been implemented within the area such as promotion of organic farming, hiring of estero rangers to regularly clean and manage waterways, and resettlement of identified Informal Settler Families (ISFs) residing along priority easement areas.

Despite their recognition of current issues on the conservation of PCRW, the LGUs failed to present empirical evidence of positive results or specific plans of action related to the conservation of the watershed especially on the upland areas, based on the CLUPs of some of the municipalities covering the watershed. Take the case of the municipality of Dinalupihan, Bataan, which covers the largest area within the PCRW. Despite the adoption of the FLUP and various strategies in their CLUP regarding the management of PCRW, they have yet to establish a dedicated MENRO, together with the needed manpower and resources who, ideally, shall spearhead the implementation of said FLUP within the municipality. These kinds of gaps in the management undermine the capacity of the watershed to provide important resources and services to the surrounding municipalities in the present and more importantly in the future.

Figure 21. 2014, 2017, and 2024 Soil Erosion Risk Maps of PCRW showing the locations of NGP Reforestation Sites.



X. RESULTS AND DISCUSSION

Current Situation in the PCRW

Soil erosion involves the removal of sediments from their original location and the transport to other locations via various media, most notably by water and runoff (Koralay & Kara, 2018). The PCRW, considered as critical watershed for sustenance of irrigation water to surrounding provinces, can be affected by issues connected to soil erosion.

Results of the land use / land cover analysis showed that land conversion has been prevalent in the area in the past decade. Most notable among these is the drastic decline in forest areas within the watershed and its degradation into sparse vegetation such as grasslands, shrublands, agricultural areas, and bare soil. The decline in forestlands also entails substantial reduction of canopy cover and more exposure to surface runoff, leading to increased erosion risk in these converted lands. Such decline in forest cover can be attributed to several factors, both natural and anthropogenic. These may include, among others, natural degradation, extreme weather disturbances, conversion to agricultural areas, or forest fires. For the latter, the data of CENRO-Dinalupihan (2021) from 2017 to 2019 alone has shown that a total of 3,045 Ha of land within PCRW has been affected by forest fires.

Increased rates of soil erosion can aggravate the natural degradation of existing forests in the watershed. Erosion strips off the nutrient-rich topsoil, weakens the infiltration capacity of the ground, and compromises the drainage capacities of streams due to siltation, thereby negatively impacting the overall health of the dominantly young secondary forests in the area (Medina, 2019; Rondal, 2005). As forestland cover diminishes, the flora and fauna hosted by the watershed are also being detrimentally affected. This kind of phenomenon can be considered as one of the contributing factors to the lack of biodiversity hotspots and the recorded overall low biodiversity in terms of floral and faunal species in PCRW as reported by CENRO-Dinalupihan (2021).

Urban sprawl, which is a common driving factor of land conversion, has also been noted within PCRW. However, results showed that its extent is generally limited compared to the other forms of land conversion mentioned above and has been mostly constrained to the lowlands and the footslopes of the mountains.

With high to very severe soil erosion risk on the footslopes and backslopes of the mountainous areas of PCRW (Figure 14), it is expected that significant amount of sediments is being eroded and transported by surface runoff towards numerous tributaries originating from these slopes. Downstream towards the generally gentle sloped low-elevation areas, the sediment-laden waters then accumulate along the three major rivers in the watershed, namely: Pinulot, Caulaman, and Almacen Rivers. As the rivers converge downstream, slope steepness diminishes, water flow loses velocity, and the capacity of the rivers to carry sediments also weakens. Hence, suspended solids in the waters get deposited into the riverbeds, causing riverbed shoaling (Pope, 2000). Evidence of high rates of erosion and river siltation can be seen from the elevated levels of suspended solids and water turbidity (20-188 NTU) recorded from the major rivers of PCRW (CENRO-Dinalupihan, 2021).

One of the ways soil erosion affects the communities within the PCRW is through enhanced flooding situation due to riverbed shoaling. This is particularly true for barangays adjacent to Almacen River as this river serves as the confluence of majority of the watershed's runoff brought by the Pinulot River from the west to south and the Caulaman River from the north. Multiple incidents of flooding in the towns of

Hermosa, Dinalupihan, and Orani in Bataan occur almost on a regular basis such as those in 2014, 2021, and 2024 (Esconde, 2014, 2024; Rita, 2021).

Relationships among Soil Erosion Variables

The RUSLE equation (3) dictates a direct relationship between rainfall intensity, slope steepness and length, and the resulting annual soil loss (Ghosal & Das Bhattacharya, 2020). For soil type, soil erodibility increases as loam and fine sand content in the soil increases (Roose, 1996). On the other hand, an inverse relationship is true for soil loss and degree of soil cover as defined by land use / cover and existing conservation measures in the area (Ghosal & Das Bhattacharya, 2020).

Rainfall and runoff act as the main medium of erosion while topographic factors affect the kinetic energy, hence the erosive capabilities of surface runoff. Soil cover influences the amount of runoff that affects the area (Ghosal & Das Bhattacharya, 2020). Therefore, for a tropical country with complex topography such as the Philippines, the abovementioned factors have significant impact in soil erosion.

These relationships of variables are evident in the spatial distribution of erosion risk categories in PCRW. The lowlands situated east of PCRW are generally under very low to moderate erosion risk categories, primarily due to the lower amount of annual rainfall received as well as shorter and gentler slopes (Figures 6, 8, 14). Although built-up areas which proliferate in this zone provide some degree of artificial, impervious soil cover, in this case, results have shown that its contribution to soil loss is overshadowed by the impacts of other natural factors mentioned.

Going towards the upland areas of PCRW, erosion risk becomes higher (i.e. high to very severe) which can be correlated to generally greater amount of rainfall, as well as steeper and longer slopes which translates to stronger erosive capabilities of runoff (Figures 6, 8, 14). What then dictates the distinction among erosion risk in the uplands is the degree of vegetative cover as represented by the land cover classification. The footslopes and backslopes of Mt. Natib and Zambales Range have relatively fewer vegetative cover as exemplified by the prevalence of bare soils and grasslands / shrublands in these areas. This contrasts with the better canopy cover provided by the forestlands on the upper elevations. Hence, areas under very high to very severe soil erosion risk rating based on Figure 14, generally located on the footslopes and backslopes of PCRW, are considered as soil erosion hotspots and should be prioritized for rehabilitation.

Soil Erosion Management for PCRW

Looking at the land cover change in the area, the scenario from 2014 to 2017 which recorded an increase in the area of NGP sites under high to very severe erosion risk can be correlated with a general decrease in vegetative cover within these NGP sites, where forest cover decreased while sparse vegetated grasslands / shrublands increased in area within this period. In contrast, the scenario from 2017 to 2024 which presented a minor decline of NGP areas under very severe erosion risk may be related to a slight recovery in forest cover from the conversion of other land cover types such as barren lands and grasslands / shrublands. This development may be attributed to several reasons, such as natural forest recovery or the possible positive impacts of reforestation efforts under the NGP.

However, the overall prevalence of high to very severe erosion risk within the existing reforestation sites in 2024 may indicate that the intended positive impact of reforestation in soil and water conservation is not yet fully realized. It is then evident that current conservation efforts for the PCRW should be intensified and optimized to effectively mitigate or lessen soil erosion risk at the soonest possible time. It is in this way that generated soil erosion risk maps can aid in management efforts, as these maps can give insights to watershed managers of possible priority zones as far as soil erosion mitigation is concerned.

A significant portion of the protected areas (PAs), where at least half of the currently dedicated reforestation areas are situated, are under moderate to high erosion risk while the rest of their areas are under very high to very severe risk. Adding this to the innate ecological and socioeconomic importance of PAs, it stands to reason that PAs should be considered as priority zones for rehabilitation and reforestation efforts to counter the potential detrimental effects of soil erosion.

Moreover, Figure 21 shows that steeply sloping, sparse vegetation areas (i.e. barren lands, grasslands / shrublands) surrounding the PAs on the footslopes and backslopes of Mt. Natib and Zambales Range are under very high to very severe soil erosion risk. Despite this, coverage of reforestation sites in these zones is currently limited. Therefore, focusing rehabilitation measures on these identified erosion-prone areas can also have substantial positive effects in terms of soil erosion mitigation.

The current lack of clear watershed-wide governance as presented in the Integrated Watershed Management Plan (IWMP) of PCRW and Protected Area Management Plan (PAMP), as well as the current degree of erosion risk in the area presents inefficiencies in the overall management of the watershed in terms of soil erosion mitigation and management. In contrast to the already-established management systems of PAs within the watershed, a comprehensive management strategy for the PCRW as a whole both on the level of the LGUs and NGAs are still on the planning phase. In particular, the IWMP for PCRW was only proposed in 2021 and has not yet fully materialized in the present. As a result, the plan still lacks key details on soil erosion mitigation, including research studies on GIS-aided modeling of water balance, soil erosion, and sedimentation using physical-based models (CENRO-Dinalupihan, 2021). Therefore, this study also aims to contribute by filling these gaps in the management plans for the watershed. Moreover, these types of GIS-based studies can be further enhanced through ground validation, as well as possible integration of new technologies such as drones, remote sensing, and artificial intelligence to enhance the accuracy and coverage of soil erosion monitoring.

However, to effectively implement the management plans, the establishment of appropriate managing bodies both on the regional and local / municipal level is of utmost importance. The PCRW covers 105 barangays from nine municipalities of three provinces. Hence, territorial and management conflicts can very much happen with these many administrative bodies involved. NGAs and LGUs, therefore, must allocate resources, manpower, and expertise for the formation of the unified Watershed Management Council to oversee the overall management of the watershed. Furthermore, all municipalities must organize dedicated Municipal Environment and Natural Resources Management Offices to efficiently implement regulations and projects within the PCRW. The NGAs and LGUs must also align current and future management strategies such as land use planning and zoning, reforestation efforts, ordinances, among others, with the results of science-based research such as, but not limited to, soil erosion risk assessment.

Conservation Strategies for Priority Zones within Protected Areas

Identified priority zones for rehabilitation within protected areas are the most ideal sites for the recovery of biodiversity within the watershed. Forestlands within protected areas which were degraded into shrublands, grasslands, and barren lands must be delineated as protected zones and must be thoroughly studied to identify most ideal species of indigenous trees that are suited to the climatological and soil conditions of PCRW and will also promote balanced growth of other existing species in the area. By expanding the natural vegetation in the area, the natural habitats of existing fauna will likewise expand, thereby promoting revitalization of population of stressed species, especially those that are identified as endemic to the area.

Conservation Strategies for Priority Zones outside Protected Areas

Moreover, identified priority zones which have high to very severe erosion risk and are situated outside of strict protection zones of protected areas can be considered for the establishment of agroforestry sites to also boost the local economy and livelihood of farmers which are being affected by watershed degradation. Studies on the most appropriate agroforestry systems to use must be first conducted to maximize soil conservation and livelihood expansion. Some of these systems that can be considered include sloping agricultural land technology (SALT) and contour hedgerow intercropping (CENRO-Dinalupihan, 2021). If practiced correctly, agroforestry systems can help in enhancing soil cover, reducing surface runoff velocity, and therefore minimizing soil erosion. Where necessary, structural interventions such as rock walls and terracing can also be implemented in conjunction with agroforestry to stabilize sloping areas.

The agroforestry systems to be used must also consider forest and grass fire hazards which are rampant in PCRW and therefore must take necessary measures to minimize possible occurrences of fires, such as the establishment of fire breaks and greenbelts made of impervious plant species in fire prone areas (CENRO-Dinalupihan, 2021). If not addressed, severe forest fires can aggravate soil erosion by removing any remaining vegetative cover over the soil and expose it to the erosive strength of rainfall.

The active involvement of various stakeholders such as People's Organizations, Indigenous Peoples (IPs), NGOs, and local farmer communities is crucial in ensuring the long-term sustainability of these agroforestry systems. Moreover, it is advantageous to capitalize on the expertise and traditional knowledge of the local farmers and other stakeholders through intensified public engagement, participatory decision-making, government incentives for favorable conservation practices, and community-focused soil conservation programs. These strategies could be facilitated through appropriate tenurial instruments such as Community-based Forest Management Agreements (CBFMA).

XI. RECOMMENDATION AND CONCLUSION

The Pinulot-Caulaman River Watershed serves an important role in maintaining ecological balance, sustaining regional agriculture, and providing the various needs of surrounding communities. However, studies have shown that there is an ongoing decline in the biophysical integrity of PCRW, negatively impacting its ecosystem functions.

One of the pressing environmental problems affecting watersheds is soil erosion, especially in watersheds in tropical climate and complex topography. If not properly mitigated, soil erosion can bring dire consequences, especially for a critical watershed with a central role in irrigation such as PCRW. These include degradation of water sources, loss of biodiversity, and decline in agriculture productivity.

The results of this study have shown that, considering the biophysical and socioeconomic attributes of PCRW, areas with steeper and longer slopes, dominantly loamy and sandy soils, abundant rainfall, insufficient land conservation practices, and land cover type having sparse vegetation are generally more exposed to high to very severe soil erosion risk. These areas are mostly concentrated on the footslopes and backslopes of Mt. Natib and Zambales Range where the dominant land use / land cover classifications are barren lands, grasslands, and shrublands.

The temporal analysis further shows a net decline in forest cover and an increase in the coverage of grasslands / shrublands between 2014, 2017, and 2024. Such scenarios may be correlated to a number of natural and anthropogenic factors, including, but not limited to, natural degradation, severe weather disturbances, or human interventions such as *kaingin.* The study also shows how these series of land cover conversions from 2014, 2017, and 2024 could have contributed to the general increase in areas under very high to very severe soil erosion risks.

Based on the results of the study, areas under very high to very severe soil erosion risk on the footslopes and backslopes surrounding the PAs should be considered as priority zones for soil conservation. These zones can be subjected to enhanced NGP and agroforestry programs to not only restore the area biophysically but also enhance the livelihood capacities of local farmers' communities. Moreover, areas inside the PAs, in addition to their generally moderate to high erosion risk, should also be considered as priority zones due to their innate bioecological significance. For these areas within PAs, delineation as protected zones and the restoration of degraded forestlands using suitable indigenous tree species should be considered to revitalize both flora and fauna biodiversity, in addition to reducing soil erosion risk.

In essence, this paper highlights the applicability of RUSLE modelling and GIS-based techniques in studying soil erosion risk of watersheds in the Philippine setting. Furthermore, techniques used in this study can also be utilized to advance the research and development needed for the proposed Integrated Watershed Management Plan of the PCRW. To verify and enhance the accuracy of these studies, the employment of ground validation as well as new technologies such as drones and artificial intelligence are highly recommended. Furthermore, intra-year assessment of soil erosion trends can be considered as further research to analyze seasonal variations on soil erosion and to account for effects of extreme weather disturbances. Likewise, conducting a similar study using rainfall data segregated based on distinct changes in rainfall patterns over decades may show trends of soil erosion in response to changes in climate patterns.

Soil erosion is a serious threat to the overall integrity of PCRW and surrounding communities. This study presents the value of data-driven, evidence-based decision-making tools in addressing soil erosion risk and the overall integrity of watersheds in different parts of the country. By incorporating these strategies into watershed management plans, the negative effects of soil erosion can be significantly reduced, and the sustainable management of our watersheds can become more attainable.

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