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Application of RMMF-Based GIS Model for Soil Erosion Assessment in Andaman Ecosystem

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Abstract: Water erosion is one of the major land degradation problems all over the globe, and its accurate quantification in different land use contexts is required in order to propose suitable conservation measures and curtail related hazards. In the Andaman and Nicobar (A&N) Islands, the land use changes due to faster urbanization and deforestation practices have led to accelerated erosion at many points around the inhabited Islands. Moreover, agricultural land uses in the A&N Islands are vulnerable to severe soil erosion, mainly due to cultivation practices along the steep slopes and mono-cropping culture. A study was conducted by establishing runoff plots in areas with different land uses to measure soil and nutrient losses and to estimate soil erosion using a semi-process-based soil erosion model, i.e., Revised Morgan Morgan and Finney (RMMF). The RMMF model was calibrated using primary data from runoff plots for the years 2019–21, validated for the year 2022, and applied in a Geographical Information System (GIS) to estimate soil erosion spatially over the Andaman ecosystem. The RMMF model simulated soil erosion during validation with a coefficient determination (R^2) greater than 0.87 as compared to measured soil erosion from the runoff plots. The study revealed that annual N, P, and K losses of 41–81%, 42–95%, and 7–23%, respectively, due to runoff from various land uses. The land use land classification analysis of the Andaman Islands revealed that about 88% of the total geographical area is under the forest and mangrove land uses, which exhibited very slight soil erosion of <5 t/ha. This 88% of forest and mangrove areas requires suitable conservation measures such as afforestation and rehabilitation/restoration of mangroves. Moreover, 6% of cultivated areas need terracing, bunding, intercropping, etc., at the highest priority in order to conserve a sustainable Andaman ecosystem. On average, the annual soil loss from the Andaman Islands is 3.13 t/ha. About 6% of the study area exceeds the soil tolerance limit of 2.5–12.5 t/ha/year, which needs suitable soil and water conservation measures at the lowest priority due to economic implications.

Keywords: erosion; conservation; islands; land use; nutrients; RMMF

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1. Introduction

Currently, the global population has reached 8 billion, creating many challenges for food security. The availability of land is a severe constraint on the need to support the food requirements of an ever-growing population. Moreover, the existing available land suffers from several types of land degradation and becomes unproductive at a faster rate. A previous study has [1] revealed that nearly 15.4% of global land suffers from moderate to severe erosion rates. It is notable that water erosion is the main contributing factor for more than 56% of land degradation; annually, 20 million hectares of land are rendered uneconomical for crop production [2]. For this reason, the ability of the land to support food security for the ever-growing population is shrinking, raising concerns around understanding those areas vulnerable to erosion, their erosion rates, the relevant spatial extents for different land uses, etc. In the global literature, various studies have highlighted threats due to land degradation, mainly the soil erosion process, under varying land uses [3–18]. The alarming findings in [19] include the fact that in India about 5334 million tons of soil detaches yearly, of which about 29% reaches the sea, 10% is deposited in reservoirs (resulting in 1–2% storage capacity loss), and 61% is displaced from one place to another. Considering the prodigious loss to the ecosystem due to soil erosion, India is on track to restore 26 million hectares of its degraded land by 2030 in order to achieve its commitment to land degradation neutrality. Soil erosion is one of the most pivotal and significant forms of land degradation, and has both ecological and economic consequences. On this point, quantification of soil erosion, assessing permissible rates without affecting crop productivity, and planning conservation measures represent major challenges for all stakeholders working on various land- and water-related subjects.

In this path, research works to understand the erosion process were first initiated in the early 1930s [20] and proceeded with its quantification and modelling during the 1940s [21,22]. There are many approaches, including runoff experimental plots or silt fences [23,24], landscape evolution models [25], and other models [4], to measure and estimate soil erosion. Soil erosion and runoff can be measured accurately using runoff plots at the field scale. However, they have many practical limitations, being tedious, laborious, and expensive, and additionally generate point-based data valid for only the point locations where the experiments were conducted. To overcome the limitations of runoff plot measurements, a well-known soil erosion model, the USLE (Universal Soil Loss Equation) [26], and its subsequent revisions (RUSLE) [27] have occupied the literature, being applied all over the world. Other models to describe water erosion empirically include the AGricultural Non-Point Source Pollution Model (AGNPS) [28], Water Erosion Prediction Project (WEPP) [29,30], Unit Stream Power-based Erosion Deposition (USPED) [31], Water and Tillage Erosion Model and Sediment Delivery Model (WaTEM/SEDEM) [16], and Rangeland Hydrology and Erosion Model (RHEM) [32]. Despite the wide applicability of empirical models, they are not recommended solely for estimating soil erosion, as they lack the ability to describe water erosion for different climates due to their empirical nature.

Process-based models such as the Areal Nonpoint Source Watershed Environment Response Simulation (ANSWERS) [33], Kinematic Runoff and Erosion Model (KINEROS) [34], Chemicals, Runoff, and Erosion from Agricultural Management Systems (CREAMS) [35], Environmental Policy Integrated Climate (EPIC) [36], EROSION-3D [37], Limburg Soil Erosion Model (LISEM) [38], European Soil Erosion Model (EUROSEM) [39], Sealing and Transfer by Runoff and Erosion related to Agricultural Management (STREAM; [40]), Pan-European Soil Erosion Assessment (PESERA) [41,42], and Soil and Water Assessment Tool (SWAT) [43,44] yield accurate soil erosion estimates, however, their results are limited by the availability of large real-time input datasets. Semi-process-based models such Morgan, Morgan, and Finney (MMF) lie somewhere between process-based and empirical models; their results are more accurate than empirical models as compared to process-based models [45]. Due to the scattered geographical location, hilly topography, and densely occupied forests and mangroves in the Andaman & Nicobar (A&N) Islands, it is difficult to acquire a huge input dataset to run process-based models. Therefore, we have chosen a semi-process-based erosion model to quantify soil erosion in the Andaman Islands. The Revised Morgan, Morgan, and Finney (RMMF) model [46] was revised from the MMF model by adding a component which can simulate soil particle detachment by raindrops in terms of plant canopy height and leaf drainage. This RMMF model has proven its applicability for model soil erosion all over the world, and can be easily applied in a raster-based geographic information system [47–52].

The natural resources in the A&N Islands are profoundly afflicted by land degradation because of prolonged high erosive rains, hilly topography, poor geological formations, and other land-disturbing activities such as urbanization, mining, deforestation, etc. [53]. The limited availability of cropping land and increasing food requirement for the local and tourist population leads to unplanned cultivation practices along the slopes of the A&N Islands, which are vulnerable to severe soil erosion. Among different land uses, agricultural lands in the A&N Islands are susceptible to severe soil erosion [54]. Agricultural activities in the A&N Islands expose the topsoil to heavy rains, which transport the detachable soil particles along with their essential nutrients to the low-lying streams. This loss results in both land degradation and soil fertility issues. The land mass of the A&N Islands is not only precious in terms of agricultural and allied activities, it is important in terms of their very existence [53]. If ignored, untimely soil erosion, nutrient loss, and severe runoff from agricultural lands can reduce the land available for cultivation, and may lead to prohibitively expensive remedial measures; sometimes, it may not be possible to reclaim the degraded lands at all.

Even though most of the national and global level studies on soil erosion highlight the alarming facts on land degradation, data on soil erosion in the A&N Islands is lacking [5,55–61], and studies on soil loss from different agricultural land uses in the A&N Islands are limited. In [62], the authors studied soil loss and nutrient recycling under coconut- and areca nut-based intercropping systems at Garacharma, South Andaman. In [45], the authors carried out a soil erosion study in the Dhanikhari watershed based on selected incident rainfalls using the RMMF model with the aid of Remote Sensing (RS) and Geographical Information System (GIS). In [63], the authors used runoff plots to study soil and nutrient losses under plantations, vegetables, home gardens, and forests in the hilly terrain of South Andaman. In [64], the authors studied the characteristics of Kalpong River in North Andaman using RS and GIS. The studies on soil and nutrient losses from various land uses can be quite helpful in erosion control, sustainable crop production, and planning suitable soil conservation measures. Keeping the land as a constraint and land degradation problems in view, the present study was planned in order to quantify the soil and nutrient losses from different land uses in the A&N Islands using runoff plots and the RMMF model. The main objective of the study was to quantify the potential soil erosion rates of different land uses in the Andaman ecosystem using a semi-process-based model, then to propose suitable soil and water conservation measures based on erosion risk.

2. Materials and Methods

2.1. Study Site Description

The A&N Islands, a union territory of India, are located at geographical coordinates 6°45′–13°41′ North latitude and 92°12′–93°57′ East longitude. The Islands were mainly formed by volcanic eruptions and coral reefs. Per the 2011 Census, there are 31 inhabited out of 572 total islands, islets, and rocks, with the former encompassing about 94% of the total geographical area (8249 km^2). Both groups of islands (i.e., the Andaman group and the Nicobar group) are separated by a 150 km-wide 10° channel, and are geologically and ecologically quite distinct. In this study, soil loss experiments were conducted and spatial mapping was performed only in the Andaman group of islands, which was due to remoteness, difficulty of conducting field experiments, and other restrictions for the Nicobar Islands. The Andaman group constitutes an area of 6408 km^2, with a maximum altitude of 732 m at Saddle Peak in North Andaman. The total length, maximum width, and average width of the Andaman Islands are 467 km, 52 km, and 24 km, respectively. These Islands are volcanic in origin, and have a rolling and hilly topography ranging from steep slopes (66%) to coastal plains (<1%). The climate of the A&N Islands is 'Tropical', and South–West (May to September) and North–East (October to December) monsoons are frequent, bringing medium to heavy rains in about 8–9 months of the year. The normal rainfall is about 3179 mm with 150 rainy days [65]. Most of the rainfall in the monsoon season is lost to the sea due to the high slopes in the North to South direction together with the narrow width. There is no extreme cold or heat in the Islands; the mean maximum temperature is 30.1 °C and the mean minimum temperature is 23 °C. The Islands are situated in mid-sea; hence, the humidity percentage is high (77–80%). The soils of the study area vary from clay to clayey loam, gravel loam, and sandy loam. An area of about

37,000 ha is currently under cultivation, of which more than half is planted with coconut or areca nut [66]. The location map of the A&N Islands along with the study area and runoff plot installation sites is shown in Figure 1.

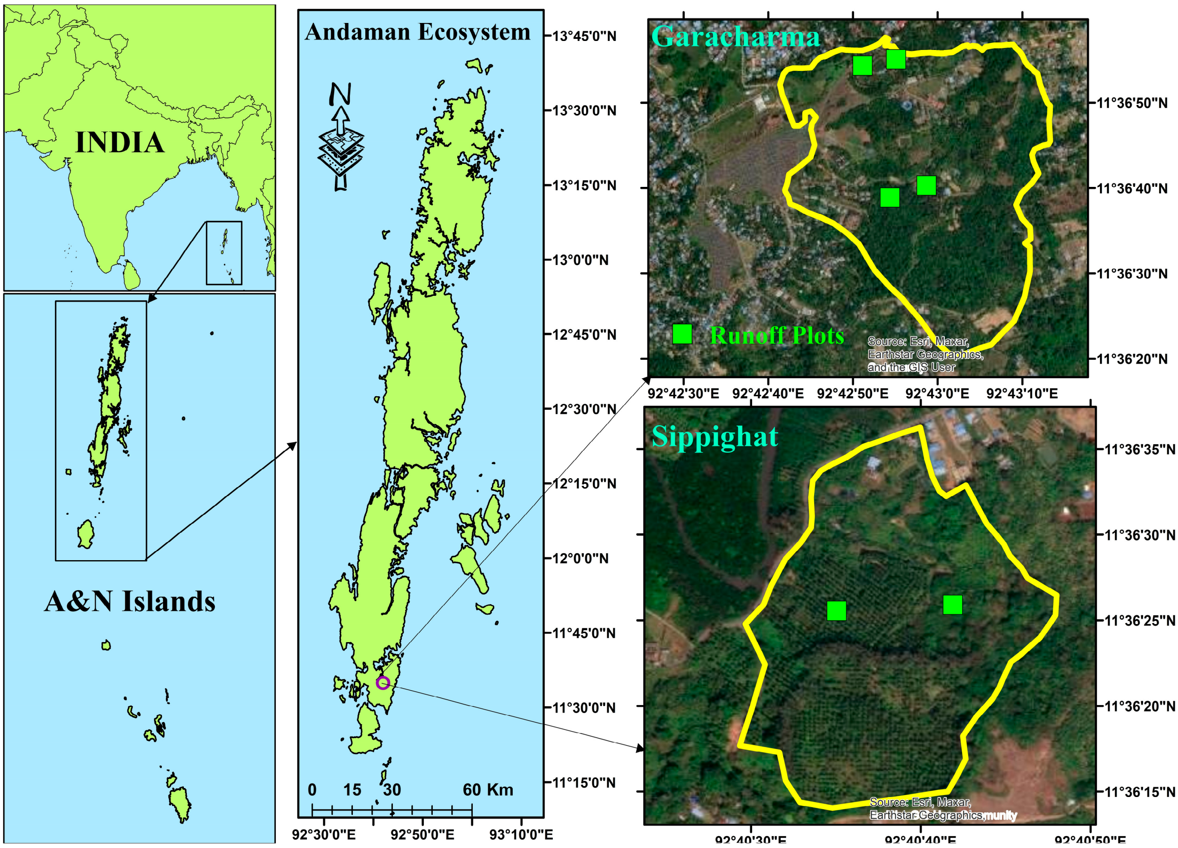

Figure 1. Map depicting study area and runoff plots.

2.2. Data Used and Source of Collection

The primary data (field observations) required to calibrate the soil erosion model were collected from runoff plots established in areas under different land use practices. Details of the primary data collected from different experiments/procedures and their duration are mentioned in Table 1. Similarly, the secondary data collected from different sources or organizations used to run the GIS-based RMMF model for the whole Andaman ecosystem are shown in Table 2.

Table 1. Field observations from runoff plots.

Data	Period	Information	Source/Instrument
Land use slope (%)	2019–2022	Runoff plot sites	Inclinometer
Rainfall (mm)	2019–2022 (Daily)	Garacharma, ICAR-CIARI	IMD Non-recording rain gauge
Runoff (Litres)	2019–2022	For erosive rainfall events of >12.5 mm	Collection cans/tanks
Soil sampling	2019–2022	pH, EC (µs/cm), Texture, Bulk density (g/cc), Porosity (%), Organic carbon (%), N (t/ha), P (t/ha), K (t/ha)	Laboratory analysis
Soil moisture (%)	2019–2022	Saturated & Unsaturated conditions	Gravimetric analysis
Infiltration (mm/h)	2019–2022	Saturated & Unsaturated conditions	Double ring infiltrometer
Silt (gm)	2019–2022	Runoff samples	Filtration of runoff samples
Nutrients	2019–2022	N (t/ha), P (t/ha), K (t/ha), OC (%)	Laboratory analysis

Table 2. Secondary data required for the RMMF model.

Data	Source	Scale/Spatial Resolution	Period	Remarks
Landsat and Resourcesat	USGS Earth Explorer, NRSC, ISRO	1:250,000	2000–2019	Land use land cover
Soil	NBSS and LUP	1:50,000	2012–2014	Reinterpreted from soil survey datasets
Topography	USGS Earth Explorer	30 m	2000	Digital Elevation Model (DEM)
Andaman Boundary	Diva-GIS	-	-	Administrative
Rainfall (mm) and Rainy days	Directorate of Economics and Statistics, A&N Islands	-	73 years (1949–2022)	Port Blair, Mayabunder, Long Island

2.3. Flowchart

The detailed methodology used to carry out spatial quantification of soil erosion in the study area is shown in the form of a flow chart in Figure 2.

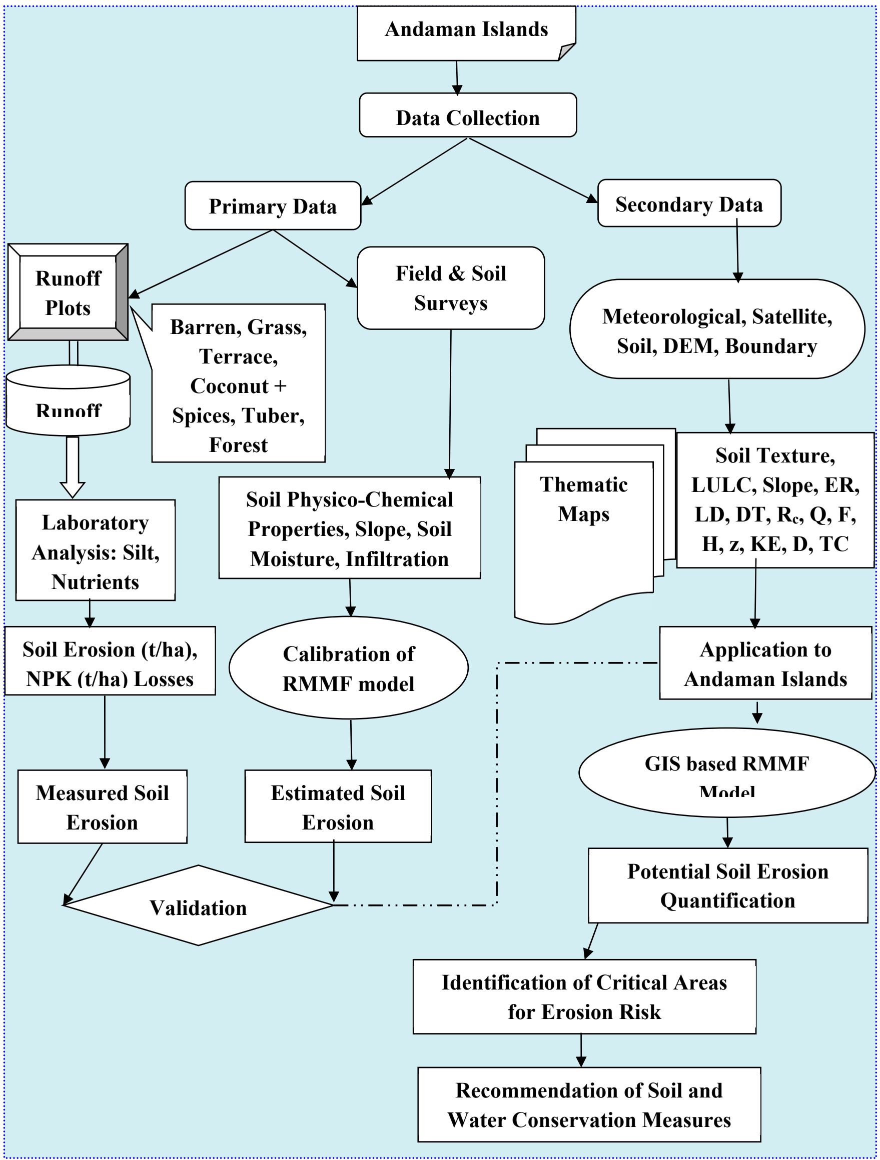

Figure 2. Methodology used to carry out soil erosion mapping for Andaman ecosystem.

2.4. Runoff Plots

To study rainfall runoff behavior and quantify the soil and nutrient losses, a total of six runoff plots, each of size 2 m × 2 m, were established in different land use areas in identified locations. Due to the study area's hilly and undulating terrain, using unit plots of 22 m length as per the USLE model was not possible; thus, 2 m × 2 m plots were established, as previously reported in the literature [45,63,67,68]. The selected land uses were Barren land, Grassland, Terrace farming (Coconut + Spices), Coconut and Spices on non-terraced land, Tuber Crops, and Forest. The reason for selecting these land uses was due to their predominance in Andaman cultivation practices. The dikes of the runoff plots were made with Aluminium sheets of 60 cm height to accommodate the splash erosion effect. Each runoff plot was connected to a 60 litre tank by a pipe to collect runoff water from the plot. The sites of the installed runoff plots and the different land uses are shown in Figure 3.

Figure 3. Runoff plots for different land uses: (**A**) Barren; (**B**) Grass; (**C**) Terrace Farming; (**D**) Coconut and Spices; (**E**) Tuber Crops; (**F**) Forest.

2.5. Revised Morgan Morgan Finney (RMMF) Model

The Revised Morgan Morgan Finney (RMMF) model [46] is the updated form of the MMF model [69] for estimating soil erosion. The detailed concept of the RMMF model is depicted in Figure 4. The RMMF model only calculates splash, inter-rill, and rill erosion. The limitation of this model is that it does not consider the gully erosion process. Most soil erosion models ignore the gully erosion process, as it is the advanced stage of erosion and adapting remedial conservation measures can have considerable economic implications. The RMMF model uses a total of 15 equations and requires 15 input variables related to climate, soil, slope, and land use to output the soil erosion (see Table 3).

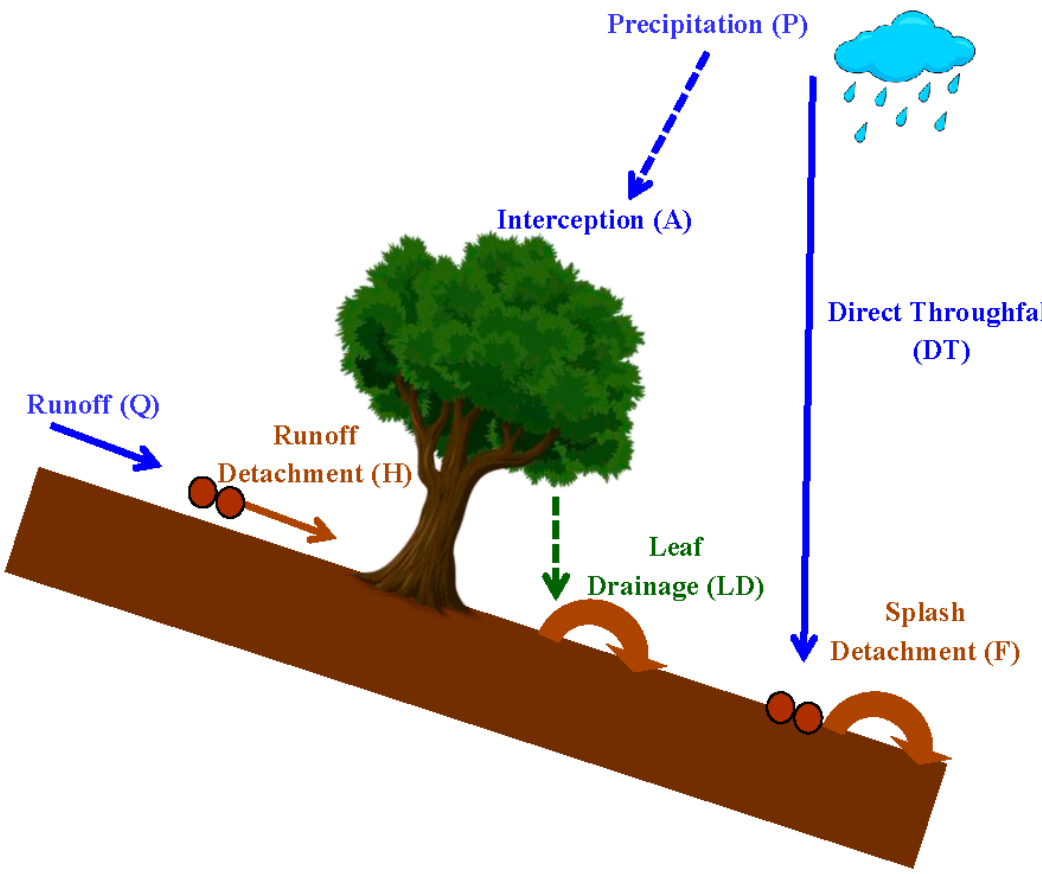

Figure 4. Conceptual principle of RMMF model (reinterpreted from [70]).

Table 3. Input data and equations of RMMF model [46,71].

	Factor	Parameter	Detail
Input Data	Climate	R (mm)	Mean annual rainfall
		R_n (Days)	Mean annual number of rain days
		I (mm/h)	Intensity of erosive rain
	Slope	S (°)	Slope steepness
	Soil	MC (kg/kg)	Soil moisture content at field capacity
		BD (Mg/m^3)	Dry bulk density of the topsoil layer
		K (g/J)	Soil detachability index (weight of soil detached from the soil mass per unit of rainfall energy)
		COH (kPa)	Cohesion of the surface soil
	Land Use	E_t/E_0 (mm/mm)	Ratio of actual crop ET to maximum crop ET
		EHD (m)	Effective hydrological depth of soil
		C	Crop cover management factor (an index ranges 0.1–1 of soil loss at a given vegetation cover compared with the soil loss at bare soil)
		CC	Canopy cover (0–1)
		GC	Fraction of vegetation ground cover (0–1)
		PH (m)	Plant canopy height
		A	Abstraction (0–1)

Table 3. *Cont.*

	Factor	Parameter	Detail
Equations	Detachment/Transportation	Effective rainfall; ER (mm)	$ER = R(1 - A)$
		Leaf drainage; LD (mm)	$LD = ER * CC$
		Direct throughfall; DT (mm)	$DT = ER - LD$
		Kinetic energy of the direct through fall; KE (DT) (J/m^2)	$KE(DT) = 29.8 - \left(\frac{127.5}{I}\right)$ [72]
		Kinetic energy of the leaf drainage; KE (LD) (J/m^2)	$KE(LD) = [(15.8 * PH^{0.5}) - 5.875]LD$ [73]
		Total energy of the effective rainfall; KE (J/m^2)	$KE = KE(DT) + KE(LD)$
		Soil moisture storage capacity; R_c (mm)	$R_c = 1000 * MS * BD * EHD\left(\frac{E_t}{E_0}\right)^{0.5}$
		Mean rain per rain day; R_0 (mm)	$R_0 = \frac{R}{R_n}$
		Annual surface runoff; Q (mm)	$Q = \mathrm{R}exp\left(-\frac{R_c}{R_0}\right)$
		Soil particle detachment by raindrop; F (kg/m^2)	$F = 10^{-3} * K * KE$
		Resistance of soil; Z	$Z = (0.5 * COH)^{-1}$
		Soil particle detachment by surface runoff; H (kg/m^2)	$H = 10^{-3} * Z * Q^{1.5} * \sin(S)(1 - GC)$
		Detachment capacity to raindrop; D (kg/m^2)	$D = F + H$
		Transport capacity of surface runoff; TC (kg/m^2)	$TC = 10^{-3} * C * Q^2 * \sin(S)$
		Annual erosion rate; E (kg/m^2)	$E = \min[D, TC]$

3. Results and Discussion

3.1. Soil Properties

A soil survey at six runoff plot sites was carried out to determine the various input properties required for calibrating the RMMF soil erosion model. The collected soil samples were analyzed at the Natural Resources Management (NRM) Laboratory of the Central Island Agricultural Research Institute (CIARI), Port Blair, A&N Islands to determine its various properties. Table 4 shows the data on soil physical, chemical, and other parameters at the studied locations. The soil texture, bulk density, and moisture content were determined using the Bouyoucos hydrometer method [74], core method [75], and gravimetric analysis, respectively. Soil texture varied from 'sandy clay' to 'sandy clay loam'. The soil was acidic (pH < 6) and electrical conductivity (EC < 1 dS/m) indicated non-saline soils. Soil properties in different land uses indicated that organic carbon ranged from 0.2–1.2% and bulk density ranged from 1.08–1.19 g/cc. The high organic carbon in Terrace Farming and Forest land uses was due to the continuous addition of organic matter due to leaf fall from the canopy of vegetation. There was little variation observed in the bulk density at various runoff plot locations, and high values were observed for both Barren lands and Grass. The Forest and Terrace Cultivation land uses had low bulk density, indicating the good quality of the soil for cultivation.

3.2. Rainfall, Runoff, and Infiltration

Several of the soil erosion studies in the literature were based on only monsoon rainfall events [45,63]. However, the rains during the non-monsoon season have a greater erosive capacity, and soils are more prone to erodibility due to their dryness. Therefore, in the present study runoff and soil erosion measurements were taken throughout the year for all erosive rain events. Rainfall data collected during the study period (2019–2022) were analysed to identify erosive rainfall events and understand the rainfall pattern in the study area. From Table 5, it can be observed that the 2020 year was considered a dry year, with total annual rainfall about 31% less than the average annual rainfall (3080 mm). It can additionally be observed that the number of erosive rainfall storms was high in 2021 and 2022 due to a greater number of rainy days. Runoff samples were collected for erosive rainfall events to assess soil and nutrient losses from different land uses at the plot scale. Erosive rainfall events were considered events which received a total amount of rainfall > 12.5 mm in a day [76].

Table 4. Physico-chemical characteristics of soil samples in different land uses.

Soil Samples	Barren	Grass	Terrace Farming	Coconut + Spices	Tuber Crops	Forest
			Physical Parameters			
BD (g/cc)	1.19	1.18	1.09	1.11	1.13	1.08
Porosity (%)	52.41	54.84	59.20	58.92	57.01	61.03
			Texture			
Sand (%)	68.53	56.01	59.93	56.00	64.91	59.22
Clay (%)	29.54	42.02	33.11	39.50	28.14	36.34
Silt (%)	1.93	1.97	6.96	4.50	6.95	4.44
Class	Sandy clay loam	Sandy clay	Sandy clay loam	Sandy clay	Sandy clay loam	Sandy clay
			Chemical Parameters			
pH	4.75	4.95	5.05	5.27	4.90	5.72
EC (dS/m)	0.04	0.05	0.12	0.14	0.13	0.13
OC (%)	0.84	0.63	1.17	0.20	0.50	1.20
			Others			
Slope (%)	18	22	8	9	11	12

Note: BD = Bulk Density, EC = Electrical Conductivity, OC = Organic Carbon.

Table 5. Distribution of rainfall during 2019–2022 in the study area.

Year	Annual Rainfall (mm)	Maximum Daily Rainfall (mm)	Rainy Days (No.)	No. of Rainfall Storms > 12.5 mm
2019	3263	166.40	133	68
2020	2354	180.00	138	53
2021	3491	107.43	162	83
2022	3027	135.00	168	83

The data regarding the total runoff (from collection tanks of runoff plots) and infiltration (double ring infiltrometer) were measured for different land uses during the study period; the average results for 2019–2022 are presented in Table 6. The rainfall and runoff behaviour of erosive storm events was analysed in terms of the percentage of rainfall, and it can be observed that the average runoff (% of rainfall) generation is higher in the Barren and Grassland land uses due to the absence or low coverage of vegetation, which leads to more erosion. The Terrace Farming and Forest land uses show low runoff generation due to high porosity and conservation benefit (Table 3). A similar runoff pattern was found in a study conducted in South Sikkim [77]. Studying infiltration patterns in different land uses/soils is important, especially in tropical regions, as the erosion may reduce the amount of infiltration by up to 93% [78]. For this reason, infiltration measurements were observed using a double ring infiltrometer in different land uses, with the maximum infiltration rate found in Terrace Farming (coconut and spices) and Forests, as more water is available for crop growth. High infiltration in the above land uses is due to continuous organic carbon addition in terms of leaf fall and high canopy coverage, improving the permeability of the soil. It can be observed that the runoff trend is inversely proportional to the infiltration behaviour. In the Barren and Grassland uses, less water enters the soil matrix due to higher runoff losses and lower porosity (Table 4).

Table 6. Runoff and infiltration measurements in different land uses.

Land Use	Runoff (% of Rainfall) *	Average Infiltration Rate (mm/h) *
Barren	26.28	6.21
Grass	24.66	11.93
Terrace farming	4.39	35.70
Coconut + Spices	9.91	25.13
Tuber Crops	17.62	23.92
Forest	3.01	36.84

* Values of runoff and infiltration are the mean values of non-erosive rainfall events over three years.

3.3. Soil Erosion

The runoff samples collected from the collection tanks of runoff plots during erosive rainfall events were brought into the laboratory and filtered by adding alum to promote settlement. The filtered silt content was considered as 'eroded soil'. The measured average soil erosion from different land uses in the study area during the three years of the study period varied from 0.9 to 16.14 t/ha/year (Table 7). The soil erosion values in different land uses followed the same runoff behaviour (Table 6). Soil erosion was lower in the Forest and Terrace Farming land uses, mainly due to the coverage of plants, which can obstruct the rainfall and reduce the splash effect of raindrops that would otherwise induce sheet erosion. Similarly low soil erosion under forests and terrace farming was depicted in a study [68] in Sikkim, Eastern Himalayas. Terrace farming is one of the most highly practised conservation measures to arrest soil erosion and reduce runoff in slopy and rugged areas such as the Andaman Islands. More runoff and soil erosion were observed for the Barren land use due to a lack of vegetation cover and the absence of soil and water conservation measures to control erosion. Similar high runoff and soil erosion was observed in [79]. It is worth mentioning that eroded soil absorbs 10–300 mm/ha/year less water than uneroded soil [80]; thus, agricultural activities face severe moisture stress conditions in eroded soil due to low infiltration rates.

Table 7. Calibration of the RMMF model and comparison of measured and estimated soil erosion.

Parameter	Barren	Grass	Terrace Farming	Coconut + Spices	Tuber Crops	Forest
MC (kg/kg)	0.17	0.22	0.50	0.39	0.48	0.51
BD (Mg/m^3)	1.19	1.18	1.09	1.11	1.13	1.08
EHD (m)	0.05	0.09	0.16	0.12	0.15	0.2
K (g/J)	0.10	0.30	0.10	0.30	0.10	0.30
COH (kPa)	3	9	3	9	3	9
Slope (%)	18	22	8	9	11	12
Et/E_0 (mm/mm)	0.05	0.45	0.85	0.70	0.80	0.90
C	1.00	0.60	0.03	0.20	0.10	0.001
CC	0.30	0.45	0.50	0.95	0.80	0.60
GC	0.70	0.10	0.45	0.10	0.20	0.30
PH (m)	5.00	0.82	6.00	20.00	12.00	10.00
A	0	0.10	0.20	0.12	0.17	0.25
RMMF modelled soil erosion (t/ha) *	17.96	10.49	1.92	5.11	11.38	1.28
Measured soil erosion (t/ha) *	16.14	9.56	1.50	6.04	8.51	0.90

* $F_{cal} < 4.96$ at 5% significance level.

The RMMF model was calibrated and validated using the measured data from runoff plots established in different land uses. The required input data used for calibrating the RMMF model are shown in Table 7. The RMMF model estimates of annual average soil erosion (t/ha) from different land uses varied from 1.28 to 17.96 t/ha/year. From Table 7, it can be seen that there is no significant difference between the measured soil erosion and the soil erosion estimated by the RMMF model (F-test). Both the measured and estimated soil erosion are in good agreement, with a coefficient of determination (R^2) = 0.87

(Figure 5). Moreover, the data are scattered well over the 1:1 line (Figure 5), indicating that the measured values are close to the values estimated by the RMMF model. Therefore, this calibrated RMMF model for the study area can be used to estimate soil erosion for the Andaman Island ecosystem in the GIS platform.

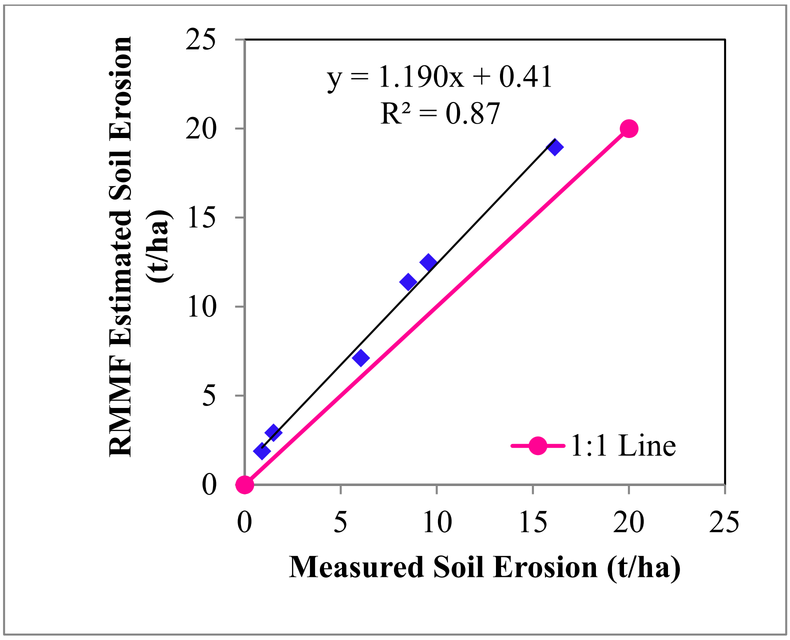

Figure 5. Scatter plot of measured and RMMF model estimated average soil erosion.

3.4. Nutrient Losses

Nutrients play a critical role in maintaining soil fertility and enhancing crop growth. Loss of nutrients occurs mainly through runoff from one place to another or one medium (land) to other media (water body). The process of erosion induces water shortages for crop growth, causes nutrient deficiencies, and reduces crop yields by 15–30% [80]. The contents of the major nutrients Nitrogen, Phosphorus, and Potash (N, P, K) and carbon under different land uses in soil (original soil near runoff plots) and silt (eroded soil) are shown in Table 8. From Table 8, it can be observed that about 41–81%, 42–95%, and 7–23% of Nitrogen, Phosphorus, and Potash (N, P, K), respectively, is lost from various land uses annually. The total N, P, K losses (t/ha) from different land uses are 0.332, 0.0022, and 0.327 t/ha, respectively. The low phosphate losses in the Islands are due to the deficiency of Phosphorus content in the parent soils of the A&N Islands. The carbon loss (%) was more than the original soil in Barren and Grassland uses, mainly due to the leaching of carbon particles due to runoff water in the eroded soil. The study [14] in Sikkim reported total N (t/year), P (t/year), and OC (t/year) losses of 6.92, 1.72, and 50.54, respectively. Similarly, [13] reported that the annual total N, P, and OC losses measured at Sikkim were 33, 5, and 267 kg/ha/year, respectively. The loss of nutrients in the A&N Islands in the current scenario was observed to be low, as these Islands practice 100% organic cultivation for sustainable and eco-friendly farming. The organic farming practices in A&N Islands not only boost crop productivity, they improve soil aggregate formation, increase porosity, and improve soil structure and water infiltration capacity. It is notable that the main contributing factors for the loss of nutrients in the A&N Islands are land disturbances due to preparing the soil before cultivation, tillage practices, land slope, cultivation along slopes, high erosive rains, etc. By reducing soil erosion due to water through adopting different conservation measures, about 1.3 to 5 times more rich organic topsoil can be saved from degradation [81].

Table 8. Relative percentage of nutrient losses in various land uses.

Land Use	Soil (in t/ha)				Silt (in t/ha)				Relative Loss (%)		
	N	P	K	OC (%)	N	P	K	PC (%)	N	P	K
Barren	0.44	0.0041	0.0741	0.84	0.085	0.0002	0.056	2.0	81	95	20
Grass	0.31	0.0039	0.0742	0.63	0.075	0.0002	0.062	1.7	76	95	16
Terrace farming	0.21	0.0016	0.0653	1.17	0.010	0.0007	0.050	0.9	53	53	23
Coconut + Spices	0.30	0.0014	0.0679	0.20	0.087	0.0008	0.056	1.1	71	42	17
Tuber crops	0.28	0.0022	0.0531	0.50	0.062	0.0002	0.049	1.2	77	93	7
Forest	0.21	0.0007	0.0668	1.20	0.013	0.0001	0.054	0.8	41	85	19
Total	1.75	0.0139	0.4014	4.54	0.332	0.0022	0.327	7.7			

OC = Organic Carbon, PC = Particle Carbon.

3.5. GIS-Based RMMF Modelling for Andaman Ecosystem

The potential soil erosion of the Andaman ecosystem was spatially modelled using the RMMF model in RS and GIS platforms. Several different thematic layers (effective rainfall, direct throughfall, leaf drainage, soil texture, slope, land use class, soil moisture storage capacity, runoff, detachment by raindrop, detachment by runoff, resistance of the soil, kinetic energy, detachment, and transportation capacity) were generated and applied in the Raster Calculator tool of ArcGIS 10.8 software [82] to map the potential soil erosion in the Andaman Islands.

3.6. Rainfall Pattern

The rainfall data from three rain gauge locations, i.e., Port Blair (South Andaman), Long Island (Middle Andaman), and Mayabunder (North Andaman) were collected for the years 1949–2022. Table 9 shows the 73-year long-term average values for the annual rainfall, number of rainy days, and mean rain per rainy day at these three locations spread over the Andaman Islands. The intensity of erosive rain (I, mm/h) for temperate, tropical, and Mediterranean tropical monsoon climates is 10, 25, and 30 mm/h, respectively [71]. Due to the non-availability of rainfall intensity data for the study area, it is assumed to be 25 mm/h for tropical climates such as the Andaman Islands. The Northern region of the Andaman group of islands, i.e., Mayabunder, receives high annual rainfall in a smaller number of rainy days as compared to other regions (Table 9). Most agricultural practices are concentrated in this region, and these soils are prone to major splash/sheet and stream bank erosion based on field observations.

Table 9. Long-term rainfall characteristics in the study area.

Location	Annual Rainfall (R, mm)	Number of Rain Days per Year (Days)	Mean Rain per Rain Day (R_0, mm)	Intensity of Erosive Rain (I, mm/h)
Port Blair	3078	144	21.37	25
Mayabunder	3484	130	26.80	
Long Island	2728	133	20.50	

3.7. Land Use Land Cover (LULC) Analysis

Supervised training was followed in the ArcGIS 10.8 [82] platform to classify the different land uses in the study area. This classification was supported by ground truth verification and Google Earth engine support. The major land uses classified in the Andaman ecosystem are Forest, Mangrove, Agriculture, Forest Plantation, Degraded Forest, Wetlands, Built-up, Degraded Mangrove, Water Bodies, Plantations, and Fallow. The land use land cover map of the Andaman ecosystem is shown in Figure 6. The data on the statistics of the identified LULC categories are presented in Table 10. It can be seen from Figure 6 that about 88% of the total area of the Andaman ecosystem is under Forest- or Mangrove-related land uses. It is apparent that about 6% of the area is under agricultural practices and 0.5% is covered by plantation crops such as coconut and areca nut (Table 10).

The major portion of the study area is occupied by the Forest and Mangrove land uses, followed by agricultural uses. The agriculture activities in the islands are mostly rain-fed, involving cropping practices on open, sloppy, unterraced, and plantation-based intercropping systems. Runoff and soil erosion from the above cultivation practices are very high in the absence of any soil and water conservation measures.

Table 10. Land use classes in the Andaman ecosystem.

LULC	Area (ha)	Area (%)
Forest	347,665	69.01
Mangroves	71,219	14.14
Agriculture	30,160	5.99
Forest Plantations	14,974	2.97
Degraded Forest	12,724	2.53
Wetlands	10,913	2.17
Built-up	6688	1.33
Degraded Mangrove	3065	0.61
Water bodies	2642	0.52
Plantations	2603	0.52
Fallow	1074	0.21
Total	503,727	100.00

The input parameters required to run the GIS-based RMMF model were assigned in terms of empirical values (Table 11) for the different derived land uses in the study area [46,71,83]. Here, larger values of EHD are observed for good vegetation cover with less surface runoff, while low values indicate more eroded areas. Similarly, higher values of E_t/E_0 represent dense vegetation areas and lower values represent for highly eroded areas with less vegetation coverage.

Table 11. Land use-based parameters used in the RMMF model.

LULC	PH (m)	E_t/E_0	C	CC	GC	A	EHD (m)
Agriculture	1.22	0.86	0.3	0.8	0.6	0.15	0.12
Built-up	0	0.05	0.60	0	0	0.50	0.05
Degraded Forest	21	0.60	0.03	0.85	0.70	0.20	0.15
Degraded Mangrove	3.50	0.50	0.02	0.84	0.79	0.23	0.13
Fallow	0	0.05	0.40	0	0	0	0.09
Forest	30	0.95	0.05	0.98	0.95	0.35	0.20
Forest Plantations	16	0.90	0.22	0.80	0.70	0.25	0.17
Mangroves	10	0.80	0.04	0.95	0.88	0.28	0.18
Plantations	15	0.72	0.25	0.70	0.62	0.26	0.15
Water Bodies	0	0.70	0	0	0	0	0
Wetlands	2	0.60	0.33	0.50	0.40	0.10	0.03

Note: PH = Height of the plant canopy, E_t = Actual evapotranspiration, E_0 = Potential evapotranspiration, C = Crop cover management factor, CC = Proportion of canopy cover, GC = Proportion of ground cover, A = Proportion of the rainfall intercepted by the vegetation or crop cover, and EHD = Effective hydrological depth of soil.

3.8. Soil and Topography

The slope map of the study area (Figure 7a) was derived from the Digital Elevation Model (DEM), which was accessed from the source as mentioned in Table 2. The Andaman ecosystem showed that most of the area has high steep slopes (0.97°) running from North to South, indicating densely forest land in keeping with real visual observations. The general rule is that if the slope is steeper, runoff generation and erosion are higher. However, in the study area, these high slopes mostly correspond to forested lands; thus, runoff generation is less and soil erosion is low due to minimal land disturbance, except in the case of deforestation. Deforestation in densely vegetated areas intensifies erosion in steeply sloped lands by as much as three-fold due to the raindrop splash effect, resulting in soil being carried towards lower areas. The soil map (Figure 7b) collected from the NBSSLUP source was reinterpreted using the available field measurements. Soil analyses were performed to determine the soil textural classes, finding that the soils in the study area varied from sandy clay loam to sandy clay. The soil-based input data (moisture content, bulk density, soil erodibility index, and cohesion) required to run the RMMF model were collected from different sources, including previously reported measurements, laboratory determinations, empirical equations, and the literature [46,71,83], as provided in Table 12. It is apparent from Table 12 that the majority (74%) of the Andaman ecosystem consists of loamy clay soil, whereas clay and loamy sand soils are each found in about 12% of the area.

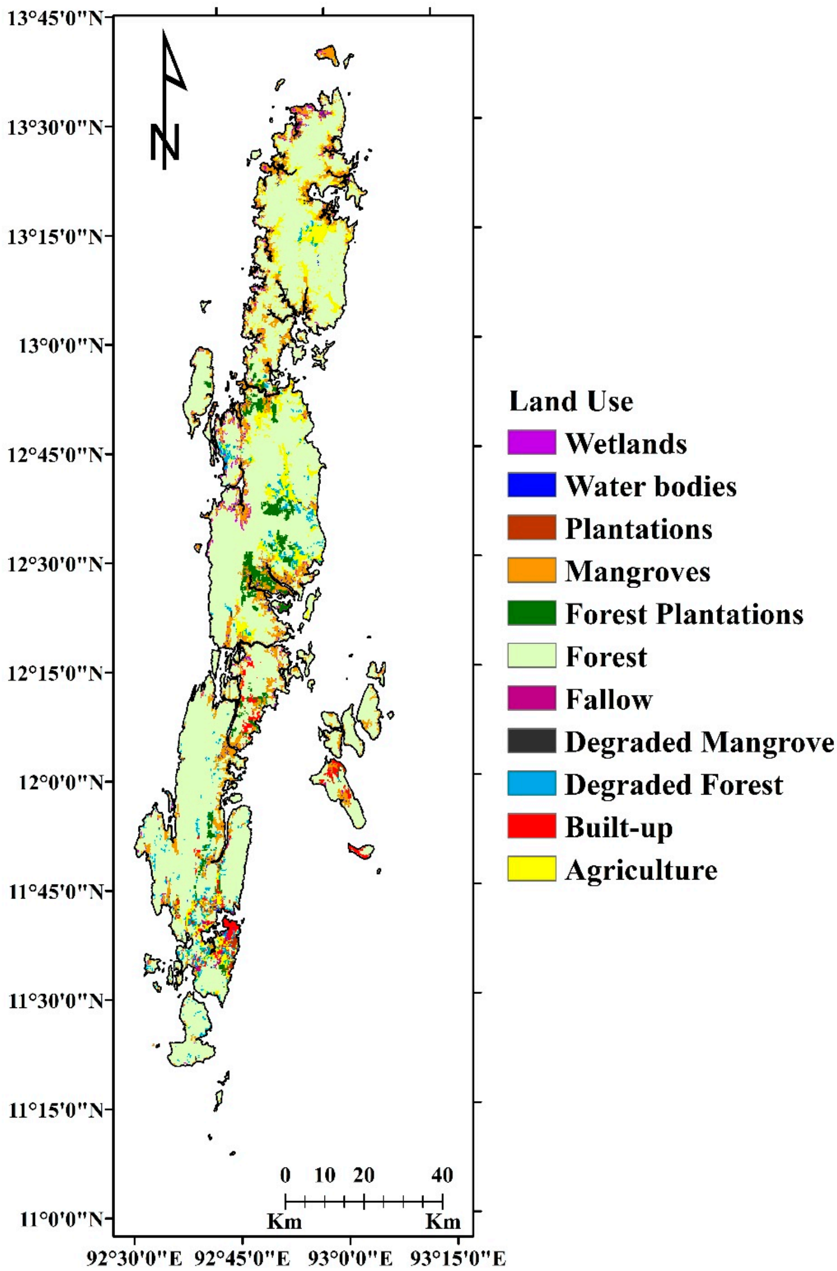

Figure 6. Land use map of the Andaman ecosystem.

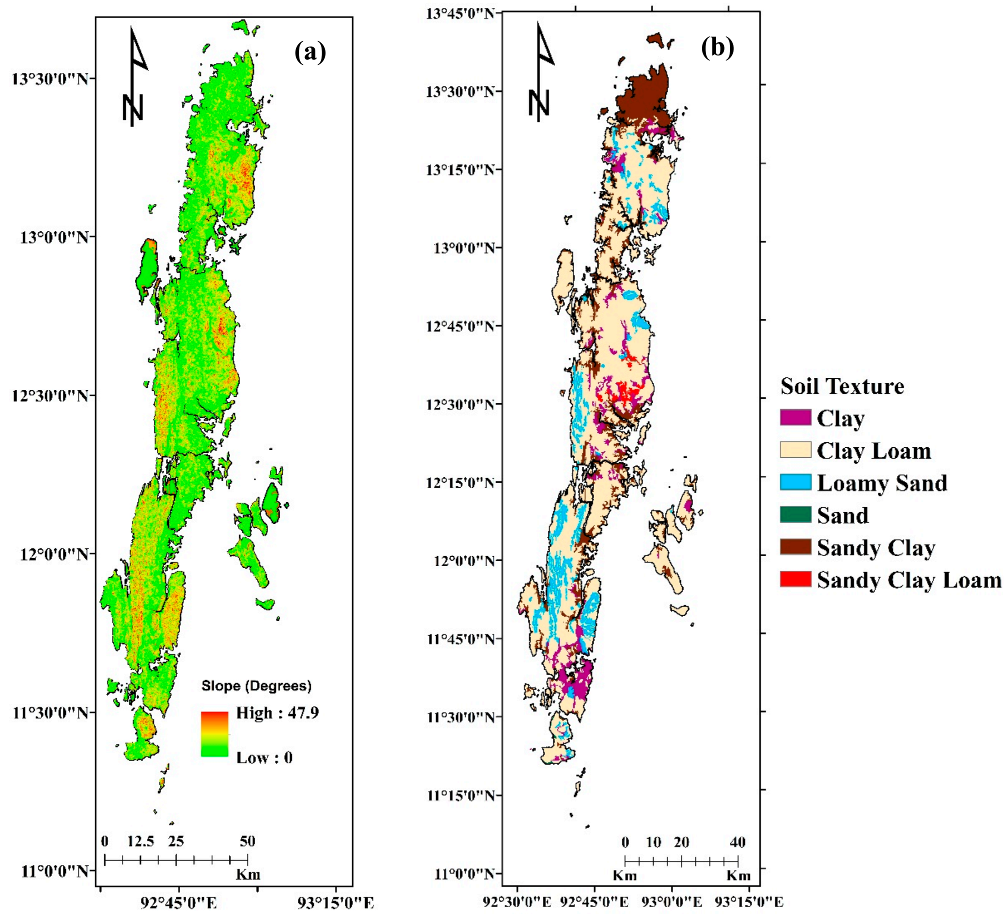

Figure 7. (**a**) Topography (slope) and (**b**) soil textural map of the Andaman ecosystem.

Table 12. Soil-based input parameters of used in the RMMF model.

Soil	Area (ha)	Area (%)	MS (% w/w)	BD (Mg/m^3)	K (g/J)	COH (kPa)
Sandy Clay Loam	5086	1.0	0.32	1.3	0.1	3
Clay	59,824	11.9	0.45	1.1	0.05	12
Clay Loam	374,539	74.4	0.4	1.3	0.7	10
Loamy Sand	59,874	11.9	0.28	1.2	0.3	2
Sand	4404	0.9	0.08	1.5	1.2	2

Note: BD = Bulk density of topsoil, MS = Moisture content, COH = Cohesion of soil, and K = Soil detachability index.

3.9. Effective Rainfall (ER)

The effective rainfall (ER) is the amount of rainfall over soil excluding interception or abstraction losses. The ER map (Figure 8a) was generated from the annual rainfall (R) (Table 9) and abstraction coefficient values (A) (Table 11). The effective rainfall reaches the ground in two ways: (i) directly through vegetation canopy gaps (direct throughfall = DT) and (ii) through stems and leaves of vegetation (leaf drainage = LD). Therefore, along with ER maps, the spatial maps for DT (Figure 8b) and LD (Figure 8c) were generated by considering the crop canopy (CC) factor values (Table 11). The effective rainfall generated in the Andaman ecosystem varies from 1550 to 3100 mm, with the highest values attributed to direct throughfall over the ground without any obstruction occurring in land uses such as Fallow and Built-up areas. At maximum, about 2120 mm of rainfall reaches the ground through leaf drainage, which happens mostly in dense vegetation areas such as Forest and Mangrove land uses.

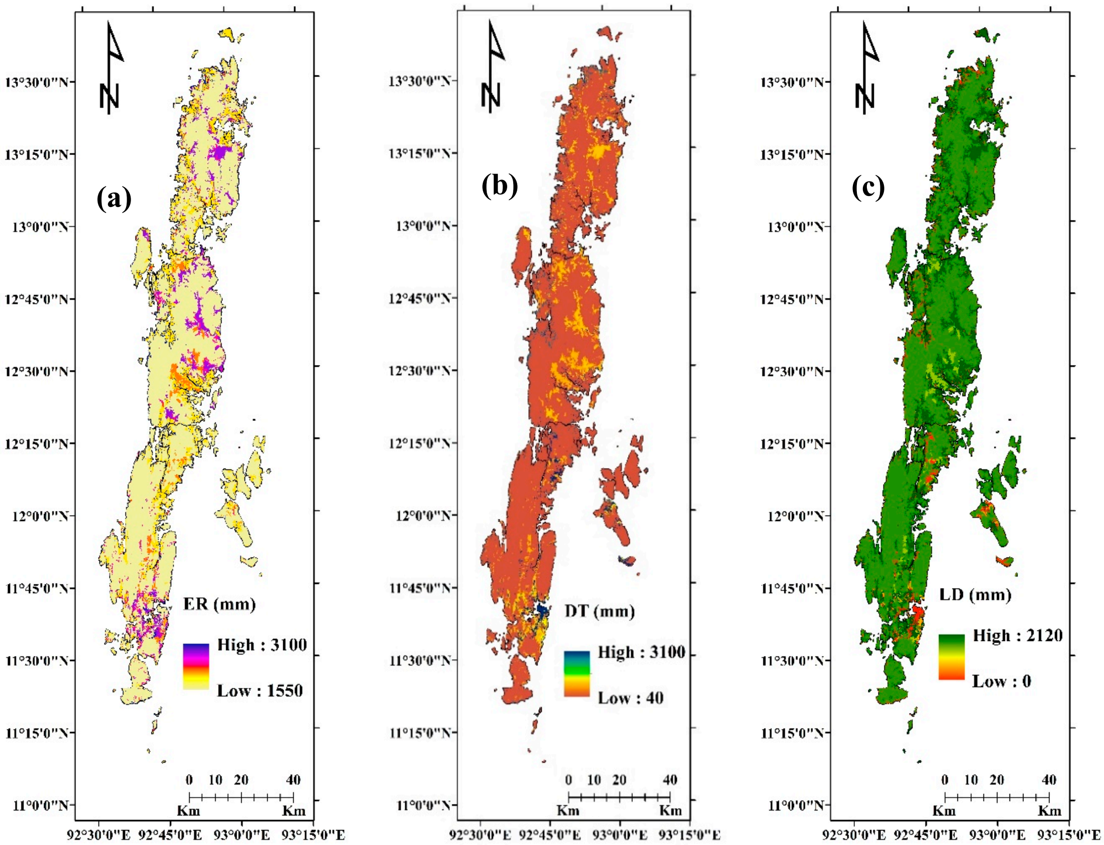

Figure 8. Spatial maps for (**a**) effective rainfall, (**b**) Direct Throughfall, and (**c**) Leaf Drainage.

3.10. Kinetic Energy (KE)

In the water phase of the RMMF model, the rainfall in terms of DT and LD exhibits the kinetic energy required to detach soil particles from the soil. Therefore, the KE of the DT and LD maps (Figure 9) were generated using Equations from the Table 3. Finally, both the KE (DT) and KE (LD) maps were summed to obtain the total kinetic energy (KE). The KE (DT) and KE (LD) in the study area were 969 to 74,592 J/m^2 and 0 to 159,299 J/m^2, respectively. A total KE of maximum 0.16 million J/m^2 in the study area is mainly attributed to high-intensity rainfall in mountainous terrain without the dense vegetation coverage of the Forest- and Mangrove-related land uses.

3.11. Soil Moisture Storage Capacity (R_c) and Surface Runoff or Overland Flow (Q)

The soil moisture storage capacity (R_c) is defined as the capacity of soil to store moisture for plant growth. It is one of the critical indicators for runoff and erosion assessment. When the R_c is lower, the runoff and erosion are higher. The thematic layer of the R_c map (Figure 10a) was generated using the data on MS, BD, EHD, and E_t/E_0 (Table 11) based on different soils and land use types. It can be observed from Figure 10a that most of the high R_c values were located on Forest soils with shallow soil depth. It is apparent that most of the agricultural lands and plantation areas exhibit low R_c values, mainly due to poor crop coverage and high evapotranspiration losses. Reduction in MS, BD, EHD, and E_t/E_0 values lead to low R_c values (following the direct relationship of R_c Equation in Table 3), ultimately resulting in high surface runoff and high erosion. The surface runoff process is initiated when satisfying the R_c [84]. The surface runoff map (Q) (Figure 10b) was generated using the R_c map and data on annual rainfall and rainy days. The maximum 'Q' generated in the study area is about 3100 mm, which was the case for very high erosive rain events on steep slopes and for open lands where the interception losses and infiltration are minimal.

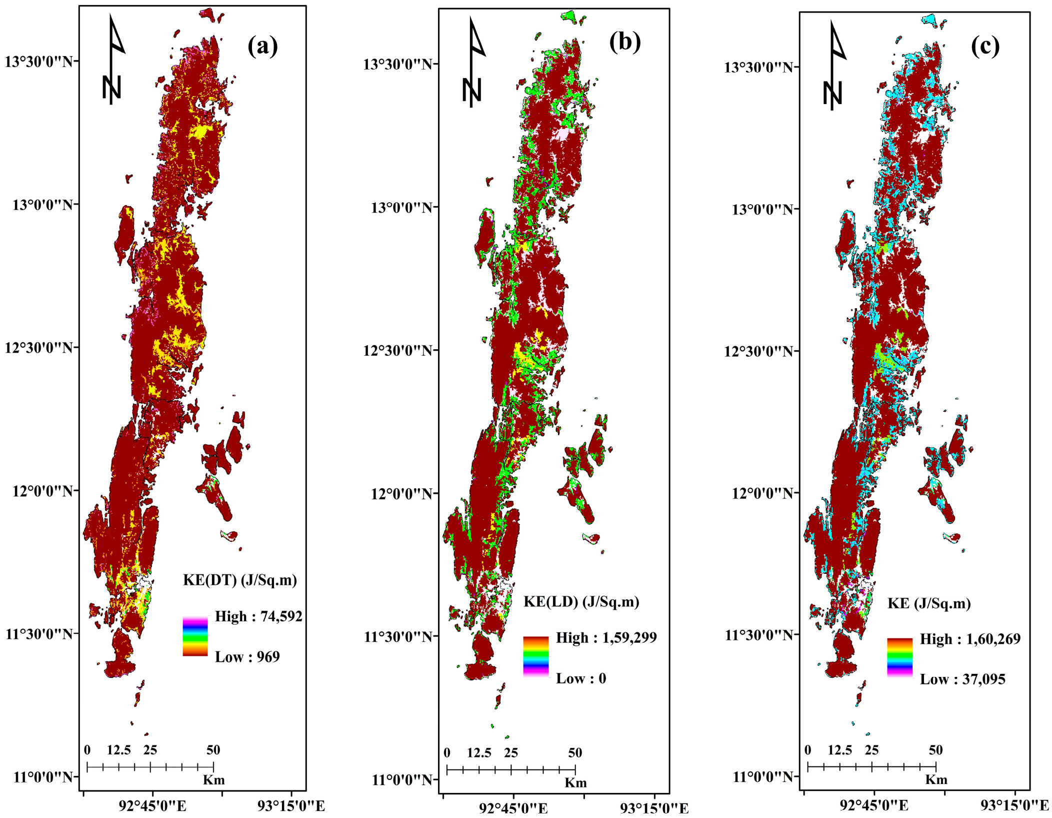

Figure 9. KE of (**a**) Direct Throughfall and (**b**) Leaf Drainage; (**c**) total KE of effective rainfall.

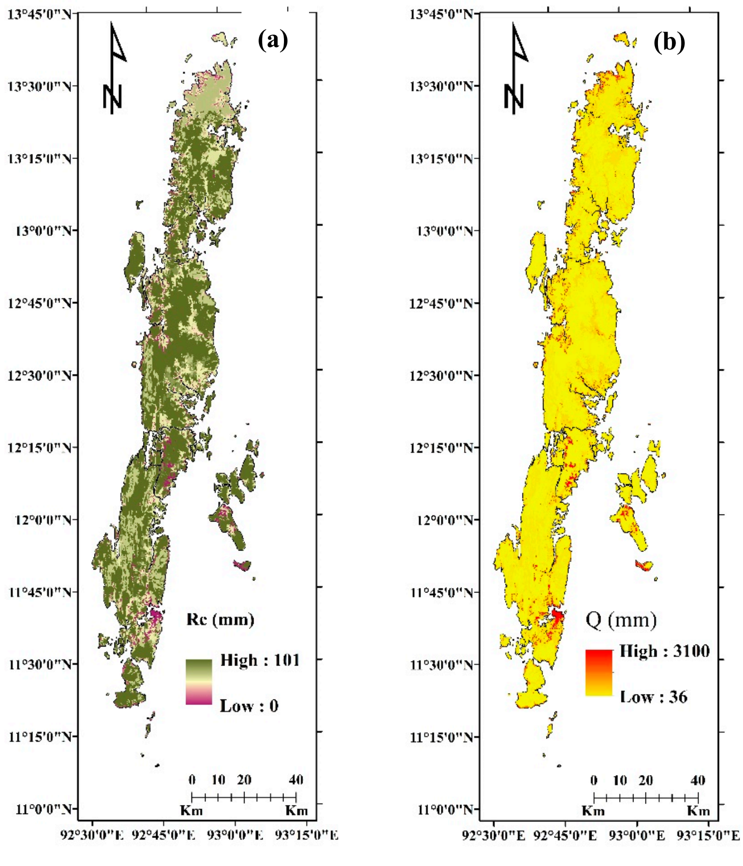

Figure 10. Spatial maps for (**a**) soil moisture storage capacity (R_c) and (**b**) surface runoff (Q).

3.12. Detachment by Raindrop (F) and Runoff (H)

Soil erosion occurs due to the detachment of soil particles by raindrop impact (F) and the transportation of detached soil particles by surface runoff or overland flow (H). The F map (Figure 11a) was derived using the KE map (Figure 9) and soil detachability index (K) information (Table 12). Similarly, for generating the H map (Figure 11b), the spatial maps of (Figure 7a), surface runoff (Figure 5b), cohesion of the soil surface (COH) (Table 12), and fraction of ground cover (GC) (Table 11) were used. Figure 11 reveals that F ranges from 1.82 to 192 Kg/m^2 and that H was ranges from 0.00026 to 13.03 Kg/m^2. In the study area, detachment by raindrops is higher compared to transportation by runoff. Both coarser and finer soils are more resistant to detachment due to their large particle size and the high energy required to break the adhesive and chemical bonding forces. Soils such as the loamy sand, fine sand, and loamy soils in the study are more detachable and transportable over downslopes, travelling large distances after their detachment.

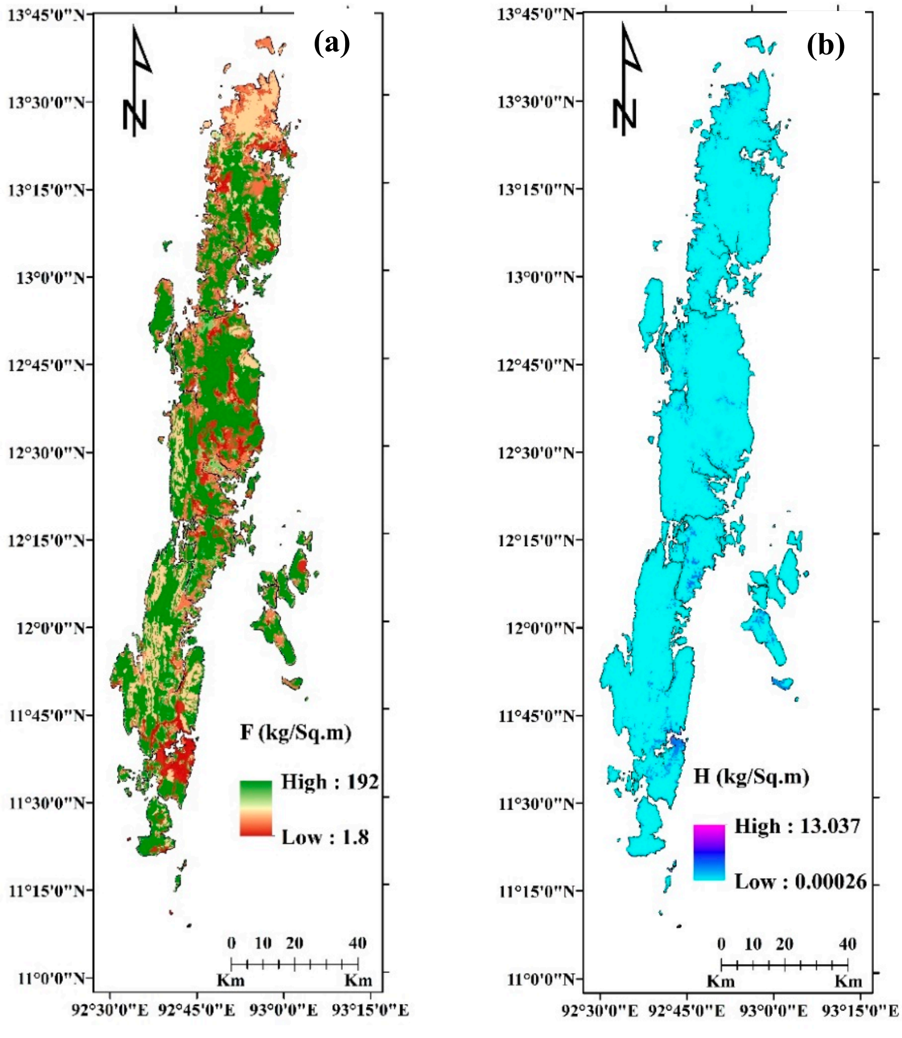

Figure 11. Spatial maps for (**a**) detachment by raindrop (F) and (**b**) runoff (H).

3.13. Detachment and Transportation

The spatial variation of the soil detachment and transportation rate is shown in Figure 12. The detachment and transportation rates ranged from >2 to <193 kg/m^2 and >0 to <423 kg/m^2, respectively. Land uses such as Forest, Forest Plantation, and Degraded Forests exhibited high detachment rates due to the low soil resistance of loose soils to detaching forces. The lowest was observed in Built-up, Fallow, and Degraded Mangrove areas. It is well known that not all detached soil particles are transported for long distances, and may be deposited immediately near the point of detachment. Similarly, for the transporting rate, the highest values are observed in Built-up, Fallow, and Wetland areas, while the lowest are found in Water Bodies, Forest, and Degraded Forest. This behaviour is mainly influenced by factors such as slope, cover crop, supporting practices, soil erodibility, and erosive conditions. In general, the TC values are lower than those of D, which is attributed to the transport of lower amounts of detached soils by rainfall drop and runoff impacts [85]. Thus, not all detached soil particles were transported in the study area; however, there were conditions whereby TC could be larger than D, for example, steep areas, compact soils, and impervious lands. This could be related to the fact that in steeply sloped lands there is a possibility of deposition taking place when the natural flow is low and the time for soil infiltration is short [85].

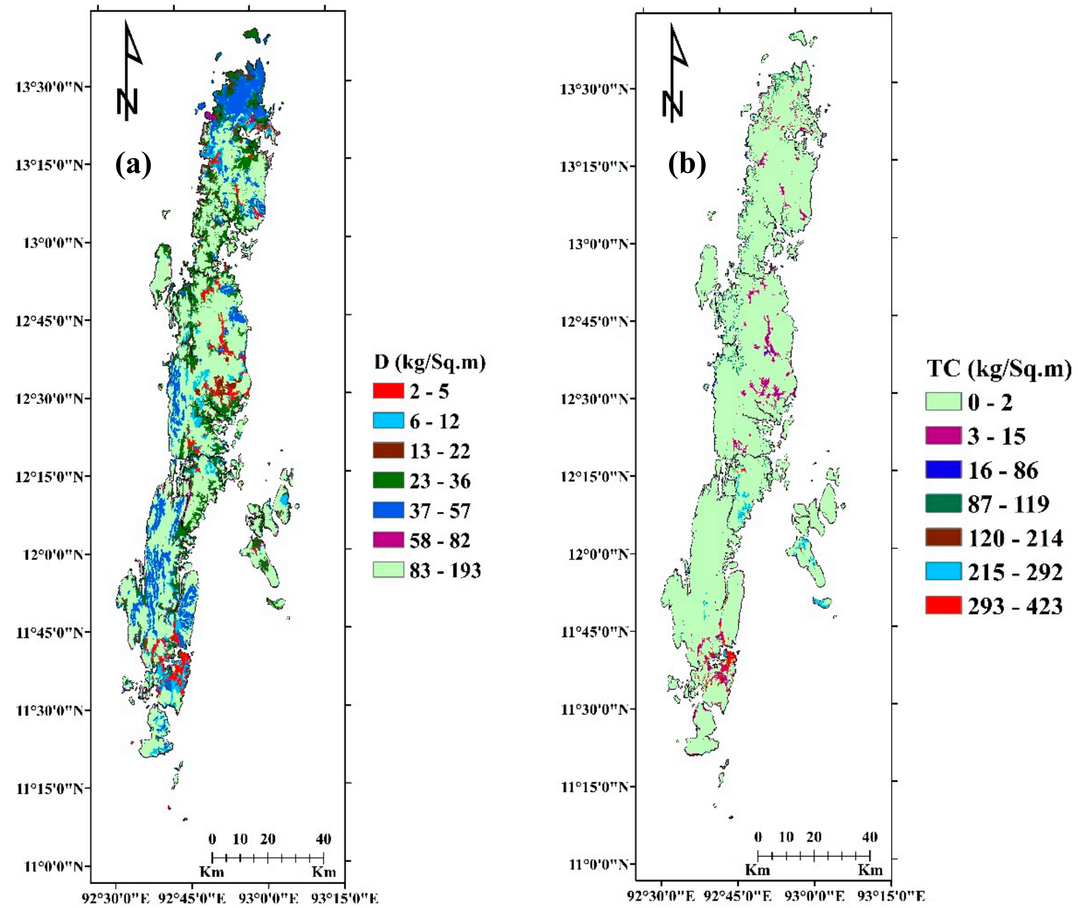

Figure 12. (**a**) Detachment and (**b**) transportation rates in the study area.

3.14. Potential Soil Erosion in the Andaman Ecosystem

The quantification of the potential soil erosion in the Andaman ecosystem was assessed by integrating various thematic maps using inputs derived from the RMMF model (Figures 6–12) in a GIS environment. The average rate of soil erosion was classified into seven soil erosion risk classes [54] for proposing soil and water conservation measures to arrest runoff and reduce soil erosion (Table 13). The potential soil erosion map of the Andaman ecosystem is shown in Figure 13. It can be observed from Figure 13 that about 88% of the total area of Andaman Islands is under very slight (<5 t/ha) to slight (5–10 t/ha) erosion risk, which mostly covers areas under the Forest and Mangrove land use classes. About 4% of the study area exhibits moderate soil erosion (10–15 t/ha/year) and around 8% shows moderate–severe (15–20 t/ha/year) to very severe (>80 t/ha/year) soil erosion risk. It is estimated that the total potential annual soil erosion in the Andaman Islands is 2.83 million tonnes, with an average rate of 3.13 t/ha/year. This is much less than India's total and average soil erosion of 5.3 billion tons and 16.35 t/ha/year, respectively [19,58]. In [13], the authors quantified the soil erosion from the Sikkim watershed as 4.18–8.82 t/ha/year. It is worth mentioning that total annual global soil erosion due to only water is about 20–30 gigatons [81].

Table 13. Soil loss classes and areal extent of erosion risk in the Andaman ecosystem.

Sl. No.	Class	Soil Erosion (t/ha)	Area (ha)	Area (%)
1.	Very slight	<5	434,454	86.6
2.	Slight	5–10	5096	1.00
3.	Moderate	10–15	22,305	4.40
4.	Moderately severe	15–20	13,414	2.70
5.	Severe	20–40	4171	0.80
6.	Very severe	40–80	6452	1.30
7.	Extremely severe	>80	15,798	3.10
	Total		501,689	

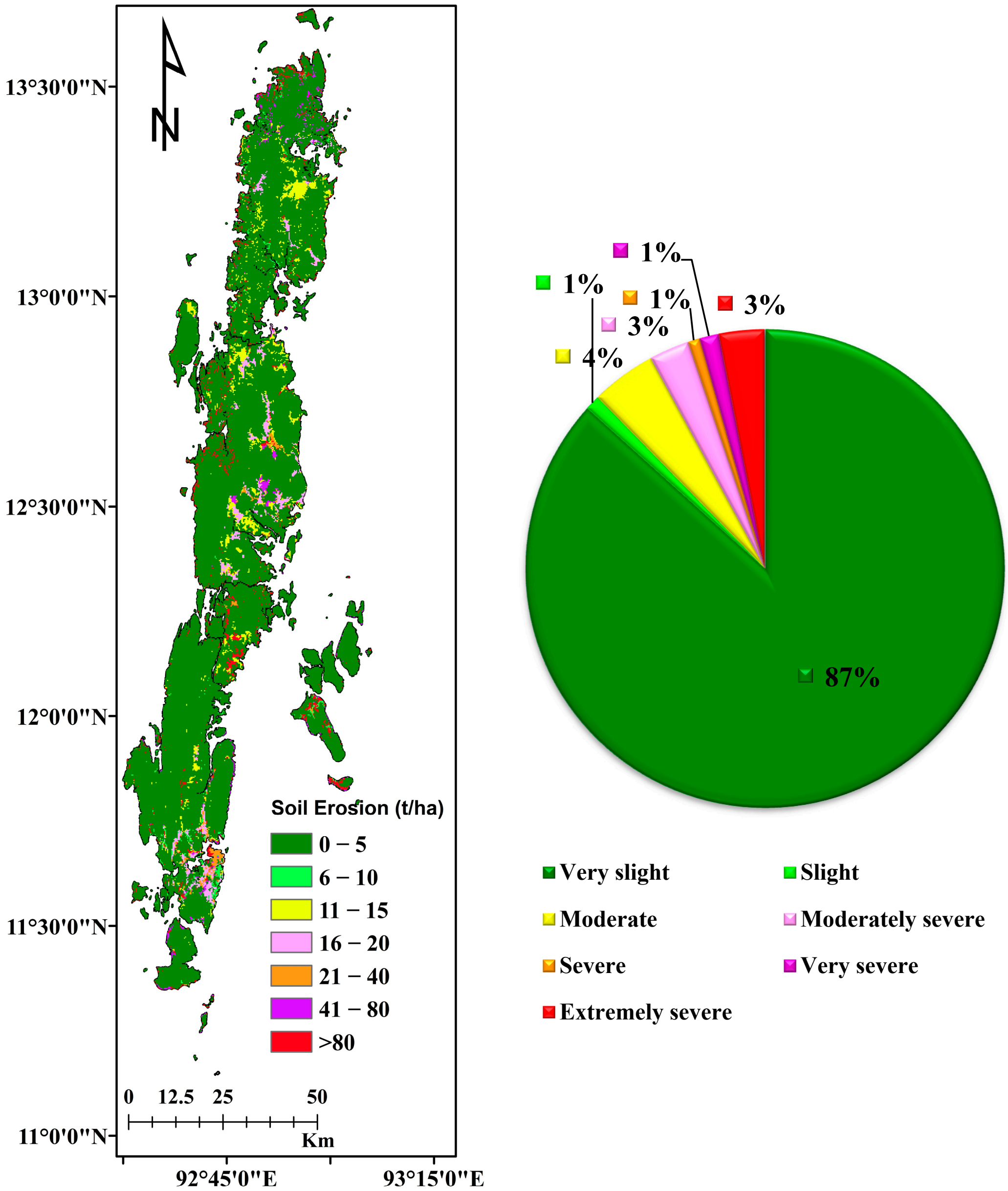

Figure 13. Potential soil erosion rate and percentage under different categories.

3.15. Land Use-Based Assessment of Potential Soil Erosion

Quantification of land use-based potential soil erosion is vital for understanding land utilization patterns, planning developmental activities, and conserving critical areas in the region. The land use-based potential soil erosion in the Andaman ecosystem is shown in Table 14 and Figure 14. It can be seen that 88% and 6% of the total area of high dense vegetation and cultivated area of Andaman Islands are found under very low (<5 t/ha/year) to moderate (>10 t/ha/year) soil erosion classes, respectively. The study of soil erosion in agricultural land use areas is very important for understanding the effect of food production systems on soil erosion and the conservation benefits accrued from the adoption of conservation practices. It can be observed that the total annual soil erosion is higher in agricultural areas (including plantations of coconut and areca nut), and is about 0.115 million tons, after only Built-up and Fallow lands. The higher rate of soil erosion, runoff, and nutrient losses from cultivated areas compared to other land uses was found in the Khanikhola watershed of Sikkim as well [14].

Table 14. Land use-based soil erosion classes in the Andaman ecosystem.

LULC	Area (ha)	Total Soil Erosion (Metric Ton)	Soil Erosion Rate (Mean ± SD) (t/ha)
Wetlands	10,717	73,618	6.87 ± 0.68
Fallow	70,301	455,675	6.48 ± 0.50
Built-up	347,437	2,125,404	6.12 ± 1.13
Agriculture	30129	115,185	3.82 ± 1.01
Forest Plantations	3034	8724	2.88 ± 1.58
Plantations	2062	4499	2.18 ± 0.87
Degraded Mangrove	12,693	22,598	1.78 ± 0.76
Degraded Forest	14,974	18,249	1.22 ± 0.76
Mangroves	2587	2667	1.03 ± 0.39
Forest	6680	6818	1.02 ± 0.31
Water bodies	1074	1074	1.00 ± 0.00
	501,689	2,834,511	3.13 ± 0.73

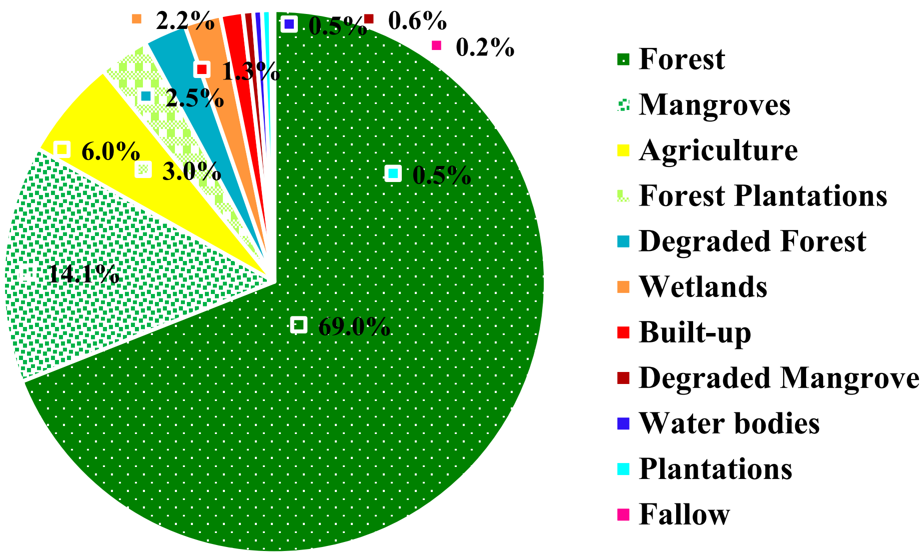

Figure 14. Land use-based potential soil erosion percentage in the A&N Islands.

The total soil erosion from Wetlands, Degraded Mangrove, and Degraded Forests is high as well (0.11 million tons), which indicates a need for planning of wetland conservation, afforestation, and mangrove restoration/rehabilitation measures to control erosion. The greater magnitude of soil erosion in certain land use areas is due to both natural and anthropogenic causes. The natural causes include poor geology and higher weathering, while the anthropogenic factors responsible for high erosion in the study area include intensive cultivation on high slopes, deforestation for developmental works, urbanization, mining, mono-cultivation practices, etc.

3.16. Soil Erosion Tolerance

In this study, a soil erosion tolerance limit of 2.5–12.5 t/ha/year was adapted for identifying critical erosion risk areas and proposing suitable conservation measures [57]. Thus, it was found that about 88% of the Andaman ecosystem has permissible soil erosion of <10 t/ha/year, which needs to be conserved immediately with suitable soil and water conservation measures as per the respective land use classes. Out of the total geographical area of the Andaman Islands, about 6% of the cultivated area exhibits soil erosion, and needs to be conserved at the highest priority to achieve self-sustaining and food-secure Islands. The cultivated lands will be lost forever if no conservation measures are taken quickly [86]. The lowest priority may be given to the remaining 6% of the study area, which exceeds the soil tolerance limit of 2.5–12.5 t/ha/year.

3.17. Island Conservation Measures

The outcomes of this study can help policymakers and organizations to propose and recommend suitable soil and water conservation measures for the fragile coastal Indian Island ecosystem of the Andaman Islands. It is a well known fact that while soil erosion cannot be brought to zero, it can be extensively reduced by adopting suitable measures. Therefore, it is recommended to seek suitable soil and conservation measures on the Islands' slopes in order to arrest runoff, reduce soil erosion, boost agricultural yields, and protect soil and aquatic resources. Most of the land uses in the Andaman Islands are dense forests, plantations of coconut and areca nut on hilly upland areas, and vegetable or paddy farms on lowlands along with home and kitchen gardens. It is recommended based on extensive field studies that the soil erosion in coconut and areca nut plantations can be reduced significantly by adopting intercropping cultivation practices such as spices (Pepper, Cinnamon, Cloves, Ginger, Bay Leaf, Turmeric, Nutmeg, etc.), local tuber crops (Tapioca and Elephant foot yam), cover crops as vegetative barriers (Lemongrass and green manures), fodder crops, and fruit trees (Banana and Pineapple). The cover crops help by reducing the splash effect of raindrops and sheet erosion by providing coverage over larger areas and on slopes. Moreover, mulching helps to conserve soil moisture and increase soil fertility through organic matter addition, ultimately enhancing crop production.

It is further noted that conservation measures such as level or inward slope bench terraces on steep areas are highly effective for arresting soil erosion in plantation-based intercropping systems [87]. The vegetable cultivation fields of the Islands, where more cultural working or tillage practices are required, yield a soil erosion of 120–130 t/ha/year, with shallow mass movements due to highly intensive storms [63]. Therefore, it is advocated that the vegetable fields of the Islands need to be cultivated with minimum or zero tillage operations, that proper soil management practices be adopted, and that contour bunding practices and trenches be used for moisture conservation in undulating terrain. It is recommended to use systematic planning in the fodder supply chain for livestock to impose restrictions on overgrazing, which is one of the factors responsible for soil erosion and land degradation.

Ultimately, systematic hydrological interventions are required to curb the soil erosion problems of major land uses with moderately severe to very severe soil erosion. In the Andaman Islands, one of the major threats of soil erosion to the water bodies/sea is the change in the water quality of water bodies; increasing turbidity in open fish ponds and deterioration of aquatic resources is a threat to terrestrial biodiversity and incurs disturbances to ecosystem services. To prevent and minimize soil erosion, farmers and other land users are urged to adopt sustainable soil management practices and conservation measures in an enabling environment. The outcome of this and similar studies suggests a suitable farming system and livelihood opportunities with minimal soil loss or land degradation in the fragile diversified Island ecosystem.

4. Summary and Conclusions

Soil erosion is one of the major land degradation and environmental problems in the A&N Islands, an archipelago of hilly and tectonically active islands. The causative factors here are mainly deforestation of high-density vegetation for construction and development, cultivation practices along slopes using hilly plantation crops, faulty agricultural practices, and mining activities related to urbanization. In the A&N Islands, quantitative data on potential average soil erosion rates are lacking. Economically, it is not possible to use conservation measures over all land uses. Therefore, the first step in addressing the land degradation issue is to obtain the necessary information on where and how much soil erosion takes place over a given region.

In this study, runoff plots of size 2 m $\times$ 2 m were established in various land uses to quantify the soil and nutrient losses at the field scale. Using the data from these field-based runoff plots, the semi-process-based RMMF model was calibrated, validated, and applied to the Andaman Islands. The results acquired from this study showed that the measured annual soil erosion from the different agricultural land uses ranged from 0.9–16.02 t/ha and that the RMMF model estimated soil erosion was in close agreement with the measured data. It was found that the highest soil erosion was in barren lands, followed by grassy areas, while the lowest was in forested and terrace cultivation areas. Analysis of nutrient samples from runoff plots indicated annual losses of about 41–81%, 42–95%, and 7–23% for N, P, K, respectively, from different land uses in the Andaman Islands.

The average annual soil erosion from the Andaman Islands was quantified as being about 3.13 t/ha. The area under Forest and Mangroves land uses exhibited very slight soil erosion of <5 t ha^{-1}, while there was severe soil erosion in Built-up and Mining areas (46.8 t ha^{-1}). About 88% of the study area fell under the soil tolerance limit of 2.5–12.5 t/ha/year, which as such requires suitable soil conservation measures, including afforestation and mangrove rehabilitation/restoration, on the highest priority basis. About 6% of the cultivated area exceeds the soil tolerance limit of 2.5–12.5 t/ha/year, and requires suitable soil and conservation measures for achieving the long-term goal of a sustainable and self-sufficient food supply for the Islands. The remaining 6% of the study area falls under the moderately severe to very severe erosion classes, and needs to be conserved on the lowest priority considering the economic implications of soil and water conservation measures for highly eroded areas. Soil erosion in the cultivated areas of the Andaman ecosystem can be reduced significantly by adapting intercropping practices in plantations, organized cultivation practices such as terracing and bunding, and growing cover crops over the slopes.

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