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Research Article

Soil Erosion Prediction Using Morgan-Morgan-Finney Model in a GIS Environment in Northern Ethiopia Catchment

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Even though scientific information on spatial distribution of hydrophysical parameters is critical for understanding erosion processes and designing suitable technologies, little is known in Geographical Information System (GIS) application in developing spatial hydrophysical data inputs and their application in Morgan-Morgan-Finney (MMF) erosion model. This study was aimed to derive spatial distribution of hydrophysical parameters and apply them in the Morgan-Morgan-Finney (MMF) model for estimating soil erosion in the Mai-Negus catchment, northern Ethiopia. Major data input for the model include climate, topography, land use, and soil data. This study demonstrated using MMF model that the rate of soil detachment varied from $<20\,\mathrm{t\,ha^{-1}\,y^{-1}}$ to $>170\,\mathrm{t\,ha^{-1}\,y^{-1}}$, whereas the soil transport capacity of overland flow (TC) ranged from $5\,\mathrm{t\,ha^{-1}\,y^{-1}}$ to $>42\,\mathrm{t\,ha^{-1}\,y^{-1}}$. The average soil loss estimated by TC using MMF model at catchment level was $26\,\mathrm{t\,ha^{-1}\,y^{-1}}$. In most parts of the catchment (>80%), the model predicted soil loss rates higher than the maximum tolerable rate ($18\,\mathrm{t\,ha^{-1}\,y^{-1}}$) estimated for Ethiopia. Hence, introducing appropriate interventions based on the erosion severity predicted by MMF model in the catchment is crucial for sustainable natural resources management.

1. Introduction

Soil erosion is the dominant cause of soil degradation at a global scale [1–3]. This is accounted for between 70 and 90% of total soil degradation [2, 4]. The adverse influences of soil erosion as a cause for soil degradation have long been recognized as a severe problem for sustainability of economic development [5]. This is because a large portion of fertile soil is lost annually which negatively influences the goal of achieving food security [3]. However, estimation of soil erosion rate is often difficult due to a complex interplay of many factors, besides the differences in scale and methodological components of the studies [6, 7]. In a country like Ethiopia, with an agriculture-based economy for more than 85% of population, having reliable soil loss data is indeed a matter of great concerns and not a matter of choice.

Regardless of the great deal of management practices undertaken aggressively in Ethiopia catchments by the government in the past 1-2 decades to reduce soil degradation, soil erosion by water is still recognized to be a severe threat to the national economy [2, 6, 7]. This indicated that the existing literature on the rate of soil erosion in Ethiopia calls for a wise decision supporting tools in order to reduce the degradation level. For instance, past studies on soil erosion in the catchments of Tigray region (northern Ethiopia) showed variability ranging from $7\,\mathrm{t\,ha^{-1}\,y^{-1}}$ [8] to more than $24\,\mathrm{t\,ha^{-1}\,y^{-1}}$ [7] and $80\,\mathrm{t\,ha^{-1}\,y^{-1}}$ [9]. According to the report by FAO [10], erosion rate is estimated up to $130\,\mathrm{t\,ha^{-1}\,y^{-1}}$ from cropland and $35\,\mathrm{t\,ha^{-1}\,y^{-1}}$ averaged over all land use types in the highlands of Ethiopia. Such discrepancies in the rates of erosion by the studies mainly attributed to changes and differences in land use, management practices, and methods employed while developing input data and their respective scale of analysis. Predominantly, previous erosion related input data were developed from simple point observation such as runoff plot, and data were interpolated through conventional method [8, 11, 12]. Such method poses many limitations in terms of cost, representation, and reliability of the resulting data [5]. Recently, to reduce such limitations geostatistic techniques that interpolate data for an entire catchment from appropriately sampled point measurements are readily available [13, 14].

Mapping through conventional methods demands an intensive data collection, which is often difficult to practice in complex terrains like in northern Ethiopia [7, 14]. The Geographic Information System (GIS) techniques can provide easy and time effective tools to map and analyze erosion input data of hydrophysical parameters. These techniques coupled with the concept of catchment priority can help in identifying areas where treatment plans should be first located. Many studies (e.g., Sharad et al. [15]; Sanware et al. [16]) revealed that GIS techniques can have a great role in characterization and prioritization of subcatchments. The catchment level assessment and mapping of hydrophysical resources can support the identification of constraints, ecological problems, and adoption of effective management practices that sustain land and water resources using integrated catchment management strategies [17]. In addition, the availability of hydrophysical parameters in a GIS map format can be used readily for erosion model running in order to understand spatial distribution of ecological problems such as soil erosion.

In many environmental studies, data inputs are measured at single points in space, even though classical statistics assume that measured data are independent and thus are not sufficient to analyze spatially dependent variables [13, 14, 18]. However, information is required for the entire catchment space, which necessitates methods that interpolate data to estimate the mean value within an area [13]. Geostatistics provides the basis for interpolation spatial variability of hydrophysical erosion model input parameters that affect runoff and soil loss [13, 14, 19–21].

To estimate soil erosion and suggest appropriate management plans, many erosion models such as Universal Soil Loss Equation (USLE) [22], Morgan-Morgan-Finney (MMF) [23], Water Erosion Prediction Project (WEPP) [24], Soil and Water Assessment Tool (SWAT) [25], European Soil Erosion Model (EUROSEM) [26], and Annualized Agricultural Non-Point Source (AnnAGNPS) [27] have been developed and used data inputs generated through GIS. Among these models, the USLE has remained the most practical method of estimating soil erosion potential for more than 40 years [28, 29], despite the fact that it has many limitations for application at catchment-scale. On the other-hand, process-based erosion models developed afterward have limitations in applicability due to intensive data and computation requirements [30]. The application of process-based models is not always an easy task since these require large amounts of information which is often not available, mainly in data scarce developing regions. The MMF model was selected to estimate annual soil loss, since this model endeavours to retain the simplicity of USLE and also encompasses the understanding of erosion processes into water and sediment phases [23]. Meaning, the MMF model was selected to be applied in this study because of its simplicity and flexibility as compared to the physical-base models and has a stronger physical base than USLE. In addition, since the MMF model is a physically based-empirical model (mix model), it needs less data than most of the other erosion predictive models [23].

Understanding the hydrophysical parameters that can influence erosion rate in a catchment is complex due to the combined nature of the natural processes and man-made features [7, 31]. Therefore, research to obtain quantitative description of hydrology/erosion in a catchment must consider these spatial heterogeneities. In order to tackle against hydrological related problems (runoff, sedimentation), accurate representation or locating the spatial distribution and variability of the influencing parameters using GIS is necessary [7, 32]. This study was aimed to derive and assess the spatial distribution of hydrophysical parameters developed using GIS technique and apply them in the MMF model for estimating the spatial variability of soil loss in the Mai-Negus catchment, northern Ethiopia. The spatial map can be used for prioritizing areas within the catchment that require immediate management measures on the basis of the severity of runoff/soil loss.

2. Materials and Methods

2.1. Study Area. The study area, Mai-Negus catchment, is located in the Tigray region, northern Ethiopia (Figure 1). The catchment has an area of 1240 ha and altitude ranges from 2060 to 2650 m above sea level [33]. In the catchment, mean annual temperature of 22°C and annual rainfall of 700 mm have been recorded (Meteorology Agency-Mekelle branch). The highest amount of rainfall (>70%) is received between July and August. Land use is predominantly arable, with teff *(Eragrostis tef)* being the major crop along with different proportions of pasture land and scattered patches of trees, bushes, and shrubs. The major rock types are lava pyroclastic and metavolcanic. Leptosols are found mainly on the very steep positions, Cambisols on gentle to steep slopes, and Vertisols on the flat areas of the catchment [34].

2.2. Research Approach. The research approach in this study consisted of five main steps. These are (i) identification of hydrophysical parameters which are inputs of MMF model, (ii) field surveys and informal discussions in order to identify representative soil sampling zones within the study catchment for soil sampling and analysis and also the corresponding vegetation cover conditions, (iii) application of empirical relations which are described by Morgan et al. [23, 35] to calculate intermediate MMF model inputs, (iv) application of geostatistic interpolation technique for spatial model inputs development, and (v) application of MMF model in GIS environment while estimating spatially distributed erosion outputs such as total overland transport capacity and soil detachment rate.

2.3. MMF Model Inputs Preparation. Input data for MMF model include rainfall (mm), land use, digital elevation model (DEM) for slope map derivation, soil texture, soil moisture content at field capacity (%w w^{-1}), soil detachability index (g J^{-1}), bulk density of soil (Mg m^{-3}), cohesion of soil surface (KPa), soil moisture storage capacity (R_c), effective

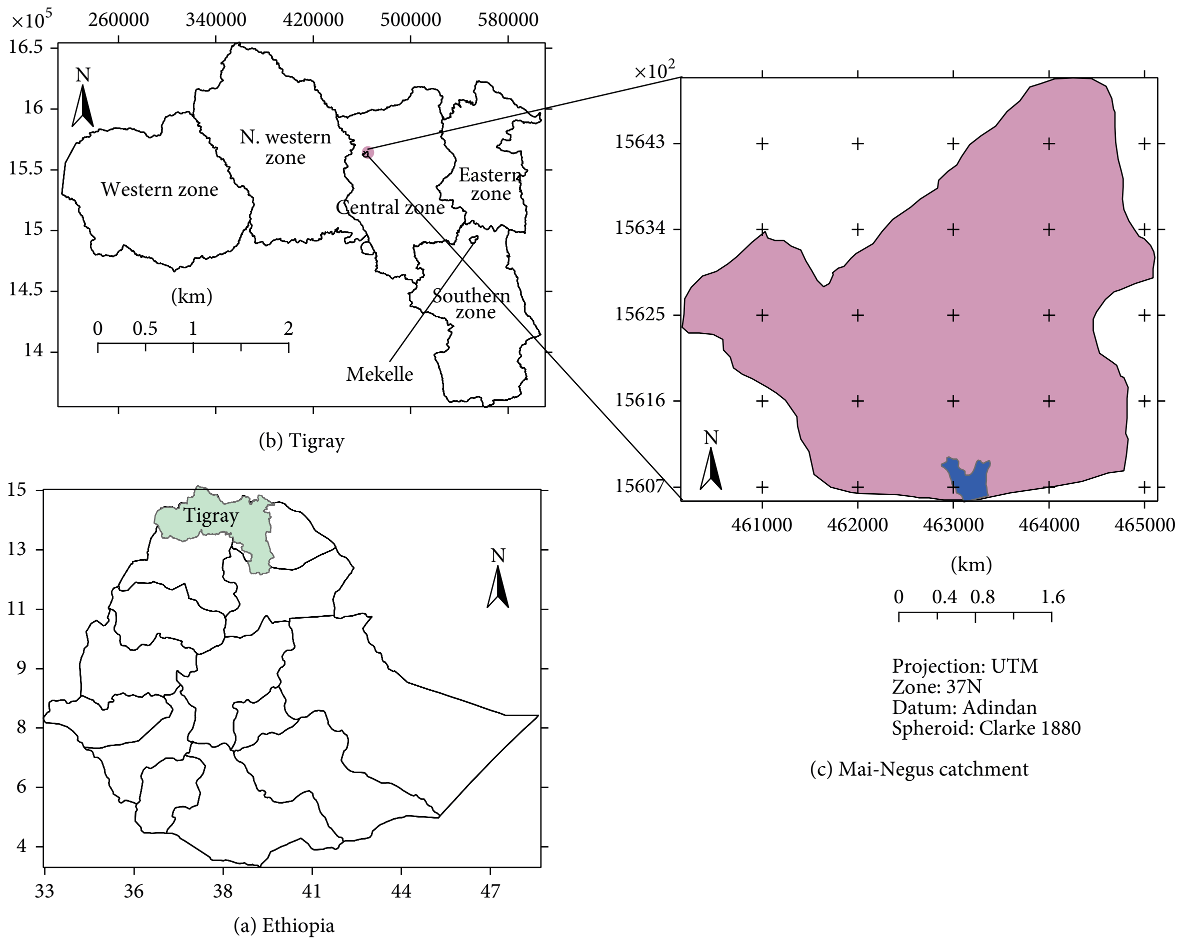

Figure 1: Study area: Ethiopia (a), Tigray (b), and Mai-Negus catchments (c). The blue colour shaded area is the reservoir.

hydrological top soil depth (EHD), and ratio of actual to potential evapotranspiration (E_t/E_o) [23, 35]. Input data were collected from different sources such as field and laboratory determination, empirical relations, and the literature. Meteorological data such as rainfall and E_t data were obtained from the meteorology station near the study area in 2009. Slope was derived from DEM developed from the topographic-map available at the Ethiopian Mapping Agency for Aksum area [33]. The map was scanned, and contours and spot heights were digitized and tagged with elevation values in a GIS environment. The vector elevation map was converted to raster and projected using the Universal Transverse Mercator 37 North (UTM-37N) reference system.

Crop and soil parameters were collected from 117 plots scattered throughout the catchment considering major land use and cover types (bush land, protected area, cultivated, abandoned fields, grazing land, mixed-forest, and residential). Supervised classification and visual interpretation of the land satellite image of November 2009 was carried out for general land use and cover mapping. In addition to this, crop covers for the different crop types and their corresponding geographic coordinates were collected using field survey in September 2009. Data related to rainfall such as rainfall intensity, number of rainy days, and total rainfall were assumed to be similar in the study catchment. The reason for having only one weather station in the study catchment is that the Office of Meteorology Agency believed that rainfall variability is negligible within such a small area regardless of the differences in elevation. Rainfall intensity was assumed at 25 mm h^{-1} which is erosive for tropical climates such as Mai-Neguse catchment because no actual intensity data was found for the study catchment. Soil detachability index (K) (g J^{-1}) was determined from the literature that corresponds to the soil texture observed in the study catchment.

2.4. Soil Sampling Zones and Sample Collection. In order to prepare MMF model soil related inputs, soil sampling that considered soil variability in the study catchment was executed. Sampling approaches that divided a field into small units (zone sampling) can capture variability and provide more information about soil-test levels compared with one composite sample collected from an entire large sampling area [36]. To reduce the number of samples and sampling costs zone sampling is suggested to provide a way to group the spatial variability of soils while maintaining acceptable information about soil properties [36]. Sampling by zone assumes that sampling areas are likely to remain temporally stable [36, 37].

In this study, the zone sampling technique (divide a field into homogenous units that allow capturing variability and provide more information) was used to collect soil samples based on previous and existing knowledge of the soil and land use systems in the entire study catchment. The natural and management factors across the landscape that influenced soil properties spatial variability were considered while identifying the soil sampling zones. Three soil sampling zones that represented the soil quality (SQ) categories, long-term land use and soil management systems, and different erosion status sites in the catchment were identified using farmers' opinions and researcher and extension experts' judgment. The data that divided the catchment into the soil sampling zones was derived during the field reconnaissance surveys in June 2009. The SQ sampling zone was entirely used for arable land in the catchment whereas the other two sampling zones belonged to all the land use systems in the catchment. The sampling zones were further subdivided into different subsampling zones considering the variability within each zone and analytical costs.

The SQ sampling zone was divided into three subzones as high, medium, and low SQ based on farmers' knowledge. They used indicators such as yield and yield component, soil depth, colour, and fertility conditions to divide into these subzones. The details on how local farmers' classified soil into different SQ categories in the study catchment can be found in Tesfahunegn et al. [38].

Eight representative long-term land use system sampling zones were identified based on farmers' historical and present information acquired in the catchment. These are (i) natural forest; (ii) plantation of protected area; (iii) grazed land; (iv) teff *(Eragrostis tef)*-faba bean *(Vicia faba)* rotation; (v) teff-wheat *(Triticum vulgare)*/barley *(Hordeum vulgare)* rotation; (vi) teff monocropping; (vii) maize *(Zea mays)* monocropping; and (vii) uncultivated marginal land. The age of the systems varied from 5-6 years for teff monocropping and 20–30 years of maize monocropping system. Average age of the other systems was about 10 years except for the plantation, grazed land, and uncultivated marginal land systems with more than 15 years.

The erosion status-based sampling zone was divided into three subzones as stable, eroded, and deposition (aggrading) sites. Information from the local farmers, extension agents, and researcher's (first author) observation on the level of topsoil depth (A-horizon), deposition, rills, pedestals, root and subsoil exposure, and gullies indicators were considered while identifying the three erosion-status sampling subzones. Those areas having A-horizon and minimum erosion indicators were considered as stable sites and the reverse of this as eroded sites. Depositional sites were also easily identified as they are mainly located in depression and flat areas with evidences of recent sediment deposition. In total, there were 14 subsampling zones across the erosion-status sites in the catchment for the soil samples collection. After doing all this identification and division, the soil sampling points in each subzone were located at the centre, considering soils in that point best represent the samples. Each sampling point was georeferenced as their distribution in the catchment is shown in Figure 2. The sampling distance was not regular, ranging from 40 to 180 m.

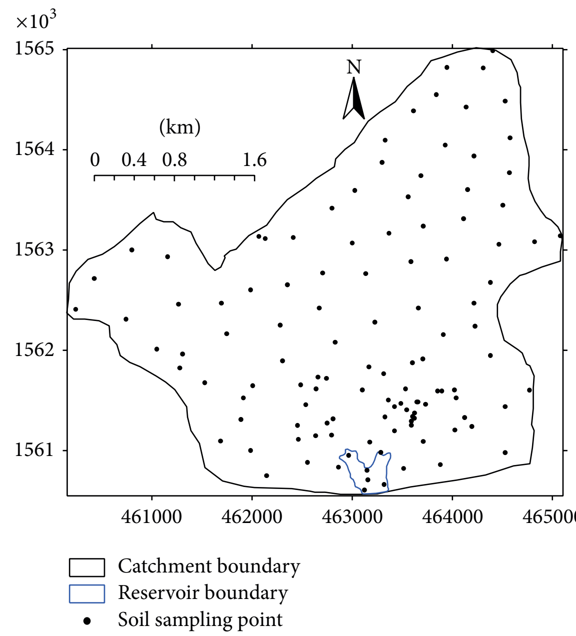

Figure 2: The distribution of soil sampling and vegetation cover points in the study catchment.

Soil samples were collected in June 2009. A total of 51 soil samples (3 subzones × 17 samples) were collected from the SQ based sampling zone. From the long-term land use systems, a total of 24 soil samples (8 subzones × 3 samples) were collected. It was also collected 42 soil/sediment samples (3 subzones × 12 samples in the catchment and 6 sampling points in the reservoir) from the erosion-status sites. The grand total of the composite samples collected across the sampling subzones was 117. Each composite soil sample was collected using 5–8 samples from each representative subsampling zone depending on the size and homogeneity of the sampling area (100–300 m^2). All the composite soil samples were collected at the soil depth of 0–20 cm (the plough depth) since this is where most changes are expected to occur due to erosion, long-term land use, and soil management practices. The composite soil samples were pooled into a bucket and mixed thoroughly to homogenize it. Finally, a subsample of 500 g from the pooled composite samples was taken and soil samples were air dried and sieved to pass 2 mm mesh sieves before analysis for soil textures. On the other hand, two undisturbed soil samples were collected from each soil sampling point for bulk density and soil moisture determination. In addition, field level observation and measurement for parameters such as effective hydrological top soil depth (m), ground cover, and cover factor were carried out from the sampling points and georeferenced.

2.5. Soil Analysis. The soil samples collected in the soil sampling zones were determined for soil texture using the Bouyoucos hydrometer method [39], soil bulk density (BD) by the core method [40], and soil moisture content at field capacity ($\mathrm{w\,w^{-1}}$) by equilibrating the soil with water through capillary action in KR box [41].

2.6. Empirical Relations in Deriving Inputs of MMF Model. Some intermediate input parameters were estimated from observed data in the catchment using the empirical relations described in Morgan et al. [23] as

$$E = R\left(11.9 + 8.7\log_{10}(I)\right),$$
$$R_c = 1000 * \mathrm{MS} * \mathrm{BD} * \mathrm{EHD} * \left(\frac{E_t}{E_o}\right)^{0.5},$$
$$\mathrm{SR} = R\exp\left(-\frac{R_C}{R_o}\right), \quad (1)$$
$$R_o = \frac{R}{R_n},$$

where E is annual kinetic energy of rainfall ($\mathrm{J\,m^{-2}}$), I is intensity of rainfall which is assumed to be $25\,\mathrm{mm\,h^{-1}}$ in tropical conditions, SR is surface runoff/overland flow (mm), R_n is number of rainy days, R is average annual rainfall (mm), R_c is soil moisture storage capacity (mm), R_o is annual rain per rain day, MS is soil moisture content at field capacity ($\mathrm{w\,w^{-1}}$), BD is bulk density of the topsoil layer ($\mathrm{Mg\,m^{-3}}$), EHD (m) is effective hydrological topsoil depth defined as the depth of soil from the surface to an impermeable or stony layer to the base of A horizon or to the dominant root base, and E_t/E_o is the ratio of actual (E_t) to potential (E_o) evapotranspiration. EHD is the top soil depth within which the storage of water affects the generation of runoff.

Intermediate maps derived on the basis of land use/cover map (Figure 3) included ratio of actual to potential evapotranspiration (E_t/E_o), permanent rainfall contributing to permanent interception, and stream flow (A) and crop cover management factor (C_f). The C_f combines C and P factors of the Universal Soil Loss Equation to give ratio of soil loss under a given management to that of bare ground with down-slope tillage, other conditions being equal. These were determined in the field. Intermediate layers derived from soil map (soil texture) included soil detachability index (K) and cohesion of topsoil (COH) that were generated using ArcGIS 9.3 software. According to Morgan et al. [23] and Dinka [35], K is defined as the weight of soil detached from the soil mass per unit of rainfall energy. The values of plant and soil related hydrological parameters are shown in Tables 1 and 2, respectively. Inputs such as plant related (e.g., EHD, A, CC) and soil related (e.g., K, COH) parameters were adopted from Morgan et al. [23] and Dinka [35], in which such values corresponded to crop type and cover conditions and soil textures observed in the field.

2.7. Application of Geostatistical Interpolation Technique. After the point data and their corresponding coordinates were entered into ArcGIS 9.3 software, maps of hydrophysical model input parameters were developed using kriging interpolation technique [42]. Ordinary kriging was selected as the preferred interpolation method for MMF model spatial inputs derivation because it was more reliable than the other interpolation methods based on the mean squared error which compares the measured values with the predicted ones. Moreover, since the spacing of the measured or observed hydro-physical input parameters were relatively sparse and randomly chosen for each subsampling zone, ordinary kriging is the best unbiased predictor for the random process at specific unsampled locations [43]. Ordinary kriging also has an additional advantage of minimizing the influence of outliers [44]. The semivariogram analyses were conducted before the application of ordinary kriging interpolation of the input parameters. This is because the semivariogram model determined the interpolation function [14]. Semivariogram models were chosen by using the cross-validation technique that compares statistical mean square error values estimated from the semivariogram models and actual values.

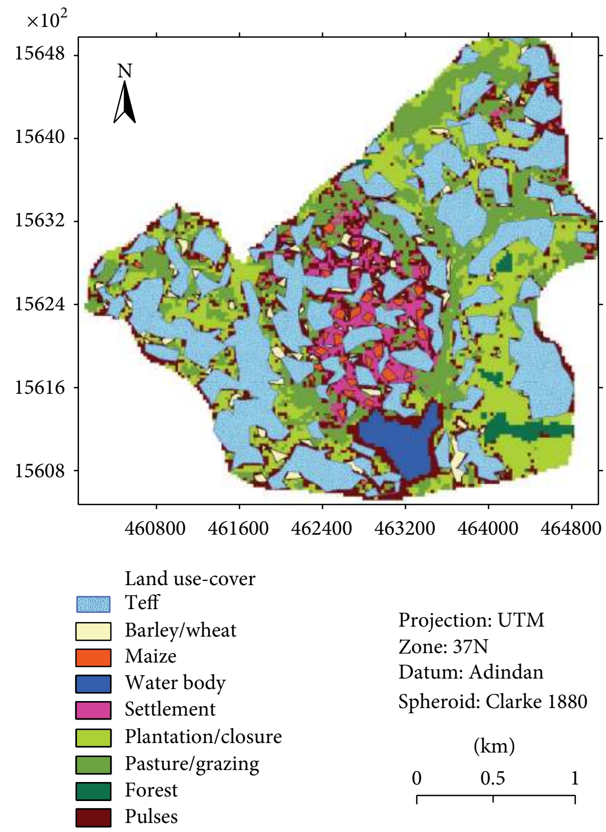

Figure 3: Land use and land cover of the study catchment.

2.8. MMF Model Application. The MMF modelling processes erosion in two phases, that is, the water and sediment phases [23]. The water phase mainly comprises of prediction of soil detachment by rain splash. It thus requires data related to intensity of rainfall (I, $\mathrm{mm\,h^{-1}}$), number of rainy days (R_n), and average annual rainfall (R, mm). After developing the different input spatial maps (layers), the rate of soil detachment by rain drop impact (F, $\mathrm{kg\,m^{-2}}$), rate of soil detachment by runoff (H, $\mathrm{kg\,m^{-2}}$), and transport capacity of

Table 1: Plant related hydrological parametersfor different land use and land cover in the Mai-Negus catchment.

Land use	EHD (cm)	A	CC (%)	PH (m)	GC (—)	E_t/E_o	C_f
Teff	5	0.15	85	0.2	0.85	0.5	0.5
Barley/wheat	12	0.3	60	0.3	0.80	0.58	0.3
Maize	12	0.25	50	1	0.75	0.68	0.25
Pulse	12	0.2	55	0.2	0.80	0.65	0.25
Grazing	12	0.2	80	0.18	0.80	0.8	0.1
Closure (grass/shrubs/bushes)	15	0.4	55	1.5	0.60	0.85	0.1
Mixed forest	20	0.5	65	1.8	0.65	0.9	0.01
Residential	19	0.1	5	0.75	0.55	0.6	0.13

EHD: Effective root depth; A: the percentage of rainfall contributing to permanent interception; CC: canopy cover fraction; PH: plant height; GC: ground cover; E_t/E_o: the ratio of actual to potential evapotranspiration; and C_f: the crop cover management factor.

Table 2: Soil related hydrological parameters values for soil texture in the Mai-Negus catchment.

Texture	K (gm J^{-1})	MS (% w w^{-1})	BD (Mg m^{-3})	COH (KPa)
Sandy loam	0.7	18.6	1.87	2
Sandy clay loam	0.3	23.7	1.72	3
Clay loam	0.4	35.38	1.48	10
Sandy clay	0.35	21.21	1.51	1
Silt clay loam	0.3	28.63	1.31	9

K: soil detachability index; MS: soil moisture at field capacity (1/3 bar) tension; BD: bulk density top soil; and COH: cohesion of topsoil.

overland flow (runoff) (TC, kg m^{-2}) are calculated in the GIS environment as follows:

$$F = 10^{-3} * K * \left(E * e^{-0.05A}\right),$$
$$H = 10^{-3} * (0.5\text{COH})^{-1}(\text{SR})^{1.5} \sin(S)(1 - \text{GC}), \quad (2)$$
$$\text{TC} = 10^{-3} * C_f * \text{SR}^2 * \sin(S),$$

where K is soil detachability index (g J^{-1}), E is annual kinetic energy of rainfall (J m^{-1}), A is percentage of rainfall contributing to permanent interception and stream flow (%), COH is cohesion of the soil surface (KPa), GC is fraction of ground (vegetation) cover (0-1), C_f is the crop cover management factor, and S is the steepness of the ground slope expressed in degree. Total particle detachment ($D = F + H$) is finally computed as sum of soil particle detachment by runoff (H) and soil particle detachment by raindrop (F) impacts. The model compares the predicted rate of splash detachment (D) and the transport capacity for overland flow (TC), and the minimum value is taken as the erosion rate (annual soil loss) estimated for fthe study catchment (Figure 4).

2.9. Model Evaluation. The percent difference (D) was used as methods for goodness-of-fit measure of model prediction. The model estimated soil loss rate in this study was evaluated with respect to the sediment deposited surveyed in the reservoir. The percent difference (D) measures the average difference between the simulated and measured values as

$$D = \left(\frac{p - q}{q}\right) 100, \quad (3)$$

where p is model simulated value and q is measure value. "A value close to 0% is best for D; however, higher values of D are acceptable if the accuracy in which the observed data have gathered is relatively poor" [45].

In addition, different studies showed that soil profile data such as degree of truncation of the top soil horizon by erosion can be used to assess the performance of models (e.g., Tamene [7]; Desmet and Govers [46]; Mitasova et al. [47]; and Turnage et al. [48]). In this study, the soil profile data was applied to evaluate the estimated erosion result by MMF model. For this purpose, areas with possible erosion processes were selected, and soil profile data related to the truncation level of the A horizon were documented in the study catchment. These data were then compared with the soil loss prediction made by the model. The main purpose was to evaluate whether the spatial pattern of erosion predicted by MMF model correlated well with the depth of soil profile data which semiquantitatively verified

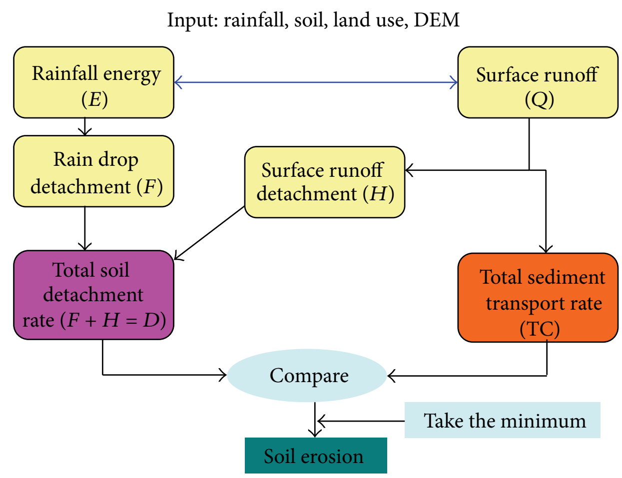

Figure 4: Flow chart depicting the methodology used for MMF modelling (source: Morgan et al. [23]).

the performance of the model. With regard to this, 10 soil profiles (pits) were identified and georeferenced and then compared to the corresponding model spatial erosion results. The MMF model result also compared with the outputs of other models which simulated in the study area and other highlands of Tigray region in northern Ethiopia.

3. Results and Discussion

3.1. Spatial Distribution of Hydrophysical Parameters Influencing Erosion. Spatial variability in slope, rainfall, vegetation, soil texture, and land use and cover are among the main factors which influence the distribution of erosion risk in a catchment [7]. Since there was only one meteorological station, weather data such as rainfall was assumed to be the same throughout the study catchment. The variability in the kriging interpolated maps of the other erosion influencing factors in the catchment is shown in Figure 5. The slope of the study catchment (Figure 5(a)) showed that the northern and eastern part of the catchment had a very steep slope (up to 77°) and slope steepness decreases in the direction to the reservoir (south of the catchment). This indicated that sources of hydrological losses as runoff and sediment yield can be higher on steep areas as compared to flat to gentle slopes provided that the other factors are similar. Such influence of slope can be explained by soil texture variability; that is, silt and clay soils dominated towards the reservoir and flat areas whereas there was a coarser texture on the steep slopes of the catchment (Figure 5(b)). This could be associated with the selective behaviour of erosion in transporting fine particles [7, 49].

Bulk density is higher (up to 1.90 Mg m^{-3}) in the steep slopes with poor vegetation cover and soil management practices and decreased to about 1.10 Mg m^{-3} around the reservoir and valley which are located at the foot-slope of the catchment (Figure 5(c)). From this figure, it is possible to observe higher erosion on areas dominated by higher bulk density as they are located on the steep slopes, low SQ, eroded sites, and marginal land soils and soils with poor vegetation cover. An increase in bulk density can negatively affect the circulation of air, water, and plant nutrients and their root system and in-turn raises rate of soil erosion [41, 50]. Such higher BD increases surface runoff which is the driving force for soil loss by decreasing soil infiltration and soil water holding capacity [51].

The spatial distribution of soil moisture content at field capacity (MS) showed lower value in the hilly part of catchment as compared to that of flat to gentle slopes under similar management and cover conditions (Figure 5(d)). This is consistent with the report by Behera et al. [52] who reported lower values of soil parameters such as MS in the topsoil layer of hilly areas. However, regardless of the slope steepness the highest MS was found in some sites of the study catchment such as in the forest and closed pasture lands with relatively higher organic matter (data not shown). The lowest MS in the catchment was associated with low SQ, poor land use, and soil management systems (e.g., marginal land, over grazing land, and eroded sites with shallow soil depth).

The effective hydrological top soil depth (EHD) spatial map (Figure 5(e)) indicated higher values (>15 cm) in relatively better vegetation-cover areas, high SQ and stable sites, and flat to gentle slopes. The EHD values were lower (<15 cm) in marginalized areas, cultivated and degraded grazing lands. Majority (78%) of the study catchment showed low EHD, indicating that such sites can be the source of higher runoff and soil loss. Similarly, the higher values (0.68 to 0.90) of E_t/E_o corresponded to forest land, whereas lower values (0.05–0.33) corresponded to agricultural areas. The intermediate E_t/E_o values can correspond to other areas such as bush land (Figure 5(f)). Such values are thus more influenced by the spatial distribution of crop cover and management factor (C_f) which ranges from 0.2–0.8 (Figure 5(g)). Areas of the catchment with higher C_f are expected to have lower E_t/E_o values and vice versa [52]. As part of the C_f factor, vegetation maintains high rates of evapotranspiration, rainfall interception, and runoff infiltration [52, 53].

The soil moisture storage capacity (R_c) calculated as a function of MS, BD, EHD, and E_t/E_o varied spatially from 5 to 79 mm (Figure 5(h)). Most of the small R_c values were located on steep slopes with shallow soil depth, poor surface cover, and marginal lands. Farmers who cultivated their land on steep slopes confirmed that they often face crop failure due to moisture stress related to low R_c. Generally, low R_c can be used as an indicator of a source of higher runoff. Such soil could be susceptible to soil detachment by raindrop and runoff impacts as a result of less vegetation cover. Reduction in the EHD (Figure 5(e)) can lead to low soil moisture storage capacity, R_c (Figure 5(h)), which resulted in higher surface runoff (Figure 5(i)).

For estimating soil detachment rate by runoff (H), understanding the spatial distribution of slope (S) (Figure 5(a)), surface runoff (SR) (Figure 5(i)), cohesion of the soil surface (COH) (Figure 5(j)), and fraction of ground cover (GC) (Figure 5(k)) are important conditions. The soil detachability by raindrop impact is also influenced by the soil detachability index (K) which showed higher values (0.79–0.98 g J^{-1}) on flat areas with coarser soils and poor soil cover and lower values (0.11–0.33 g J^{-1}) on steep slope with fine soils and good vegetation cover in the study catchment (Figure 5(l)). The lower K values on steep slope could be associated with rainfall drop impact angle which is falling to the ground surface on inclination.

3.2. Estimated Soil Loss Using MMF Model. The spatial distribution of the rate of soil detachment by raindrop (F) indicated that flat areas (south of the catchment) were exposed more to F as compared to that of hilly land (Figure 6(a)). This could be attributed to the perpendicular fall of raindrop energy (strong energy) on flat areas as compared to raindrop impact angle on inclination [2, 3]. This implied that steep slope reduces the impact of rainfall drop energy because rain drop met the soil surface on inclination. Despite this, the net detached and transported soil is almost the same on flat lands, whereas on steep surfaces more soil particles are thrown downslope than upslope during the detachment process, resulting in a net movement of material downslope [3]. Generally, the F values estimated by the model ranged

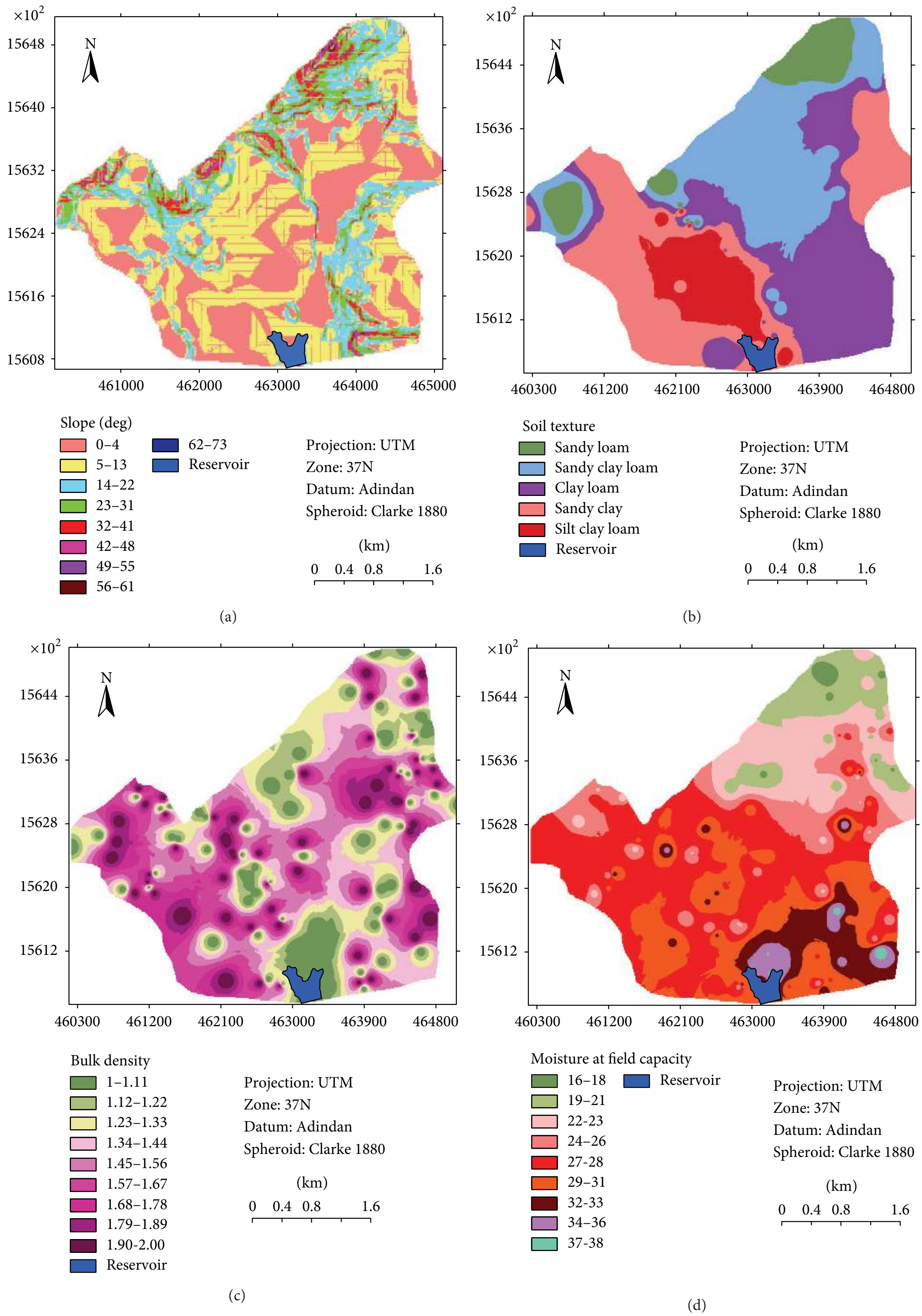

Figure 5: Continued.

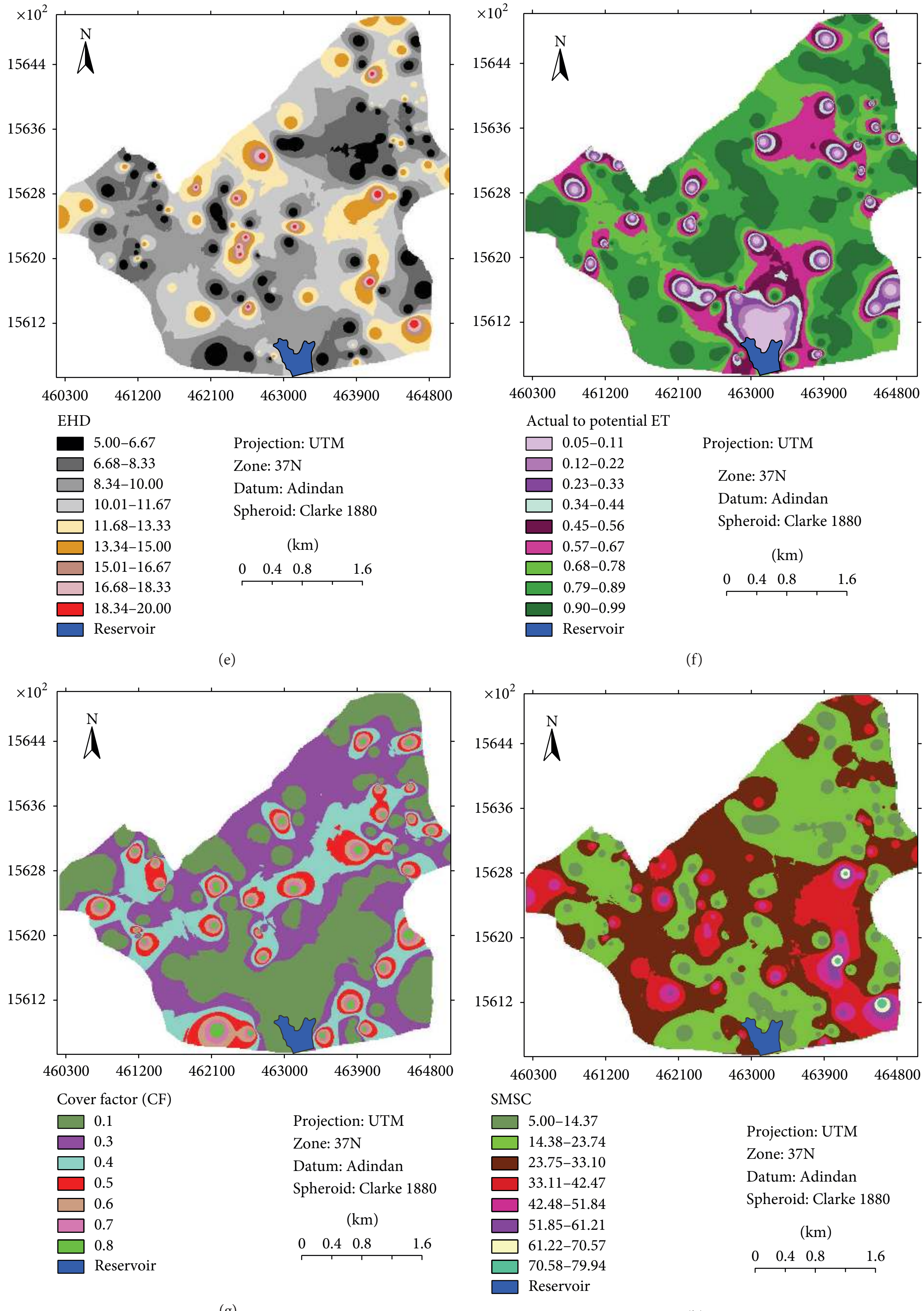

Figure 5: Continued.

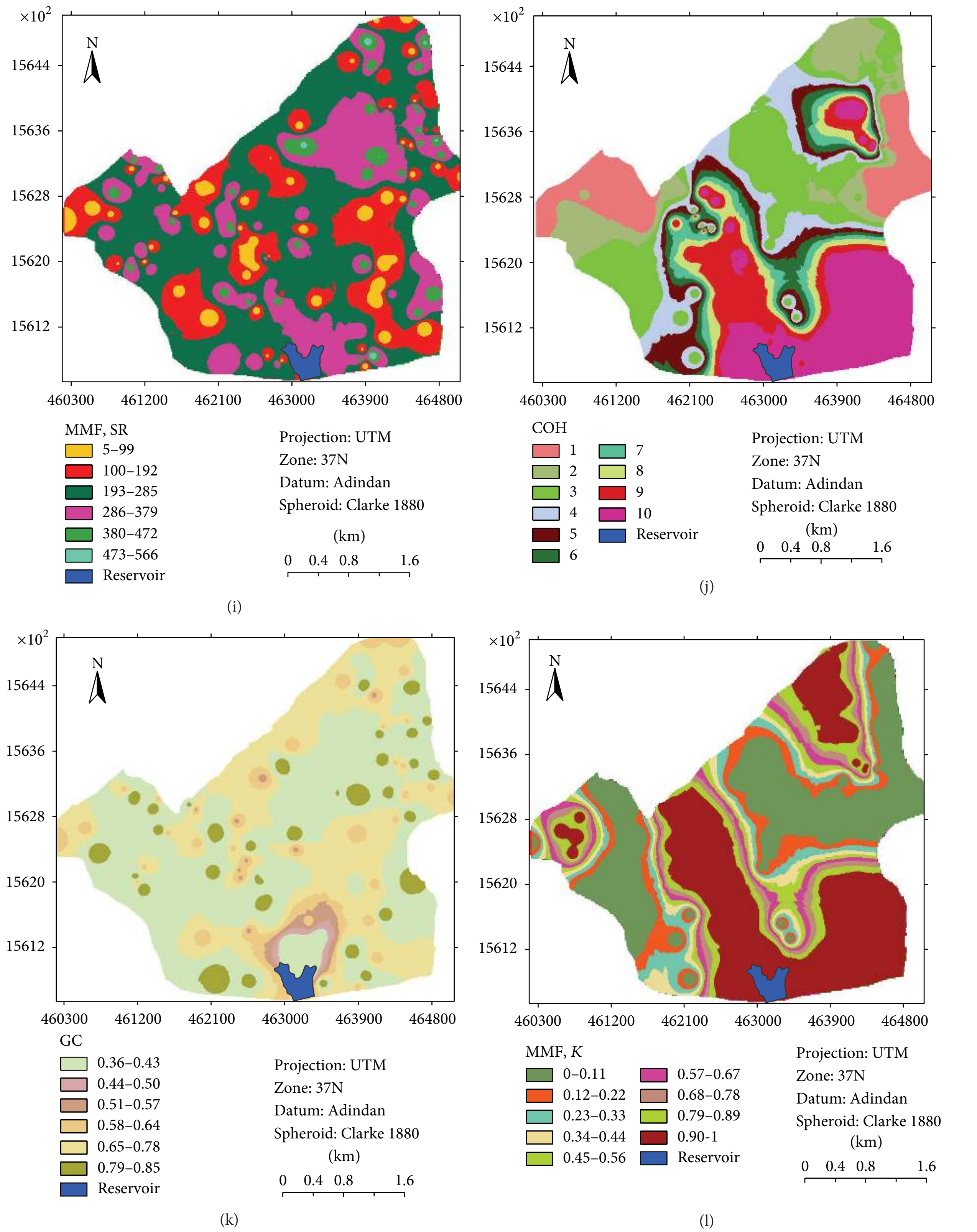

FIGURE 5: Spatial distribution of parameters influencing the hydrology/erosion of the catchment: (a) slope; (b) soil texture; (c) bulk density ($Mg\,m^{-3}$); (d) moisture at field capacity (%); (e) EHD, effective hydrological top soil depth (cm); (f) E_t/E_o, actual to potential evaporation; (g) cover management factor; (h) SMSC, soil moisture storage capacity (mm); (i) SR, surface runoff (Q) (mm); (j) COH, cohesion of the soil surface (KPa); (k) GC, fraction of ground cover (0-1); and (l) K, soil detachability index.

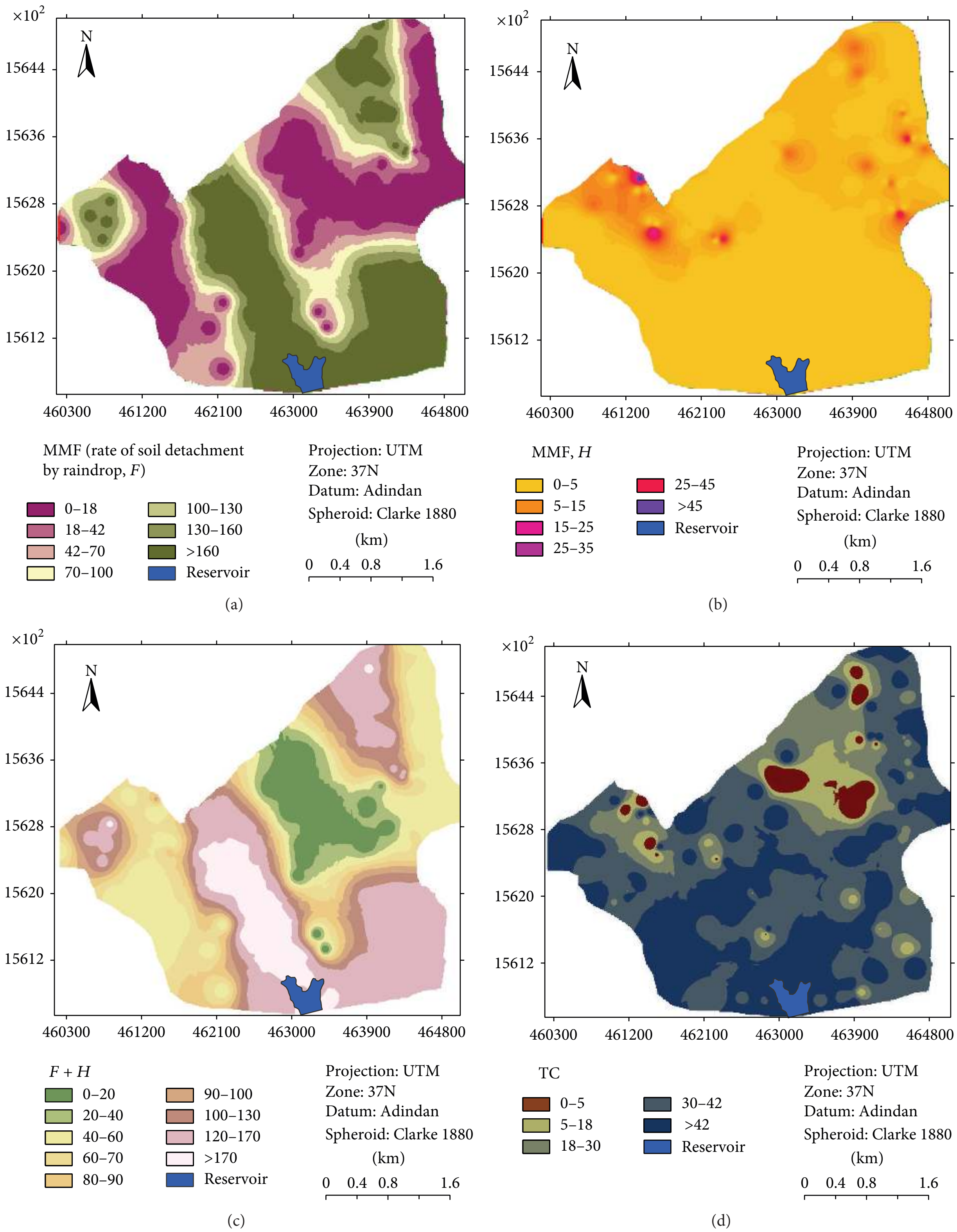

FIGURE 6: Spatial distribution of MMF erosion estimation. (a) Rate of soil detachment by rain drop impact (F) (t ha^{-1} y^{-1}); (b) rate of soil detachment by runoff impact (H) (t ha^{-1} y^{-1}); (c) total soil detachment ($F + H$) (t ha^{-1} y^{-1}); and (d) soil transport capacity of overland flow (TC) (t ha^{-1} y^{-1}).

from <18 $t\,ha^{-1}\,y^{-1}$ to >160 $t\,ha^{-1}\,y^{-1}$ in the study catchment. The plateau and valley parts of the catchment showed higher F values. Increasing soil cover and practicing zero grazing, for example, can be part of the solution for reducing the amount of soil detached by raindrops. This is because such practices can increase vegetation cover that dissipates rainfall and runoff energy [2, 3].

The soil detachment rate by runoff (H) is higher (35 $t\,ha^{-1}\,y^{-1}$) on the steep-hilly parts of the catchment (Figure 6(b)), as slope steepness increases the amount and velocity of overland flow or surface runoff (SR) (Figure 5(i)). In addition, the expansion of cropland and open grazing practices to the steep parts of the catchment could make the soil more vulnerable to soil erosion by runoff. A similar view to this study was reported by Tamene [7] who stated that on steeper slopes the soils are likely to be thinner and the flow velocity is high, which results in high runoff; whereas runoff threshold is high since water is likely to pond and infiltrate, resulting in little or no runoff on flat slope land.

The spatial variability of the total soil detachment rate ($F+H$) as a result of the summation of F and H for the catchment is shown in Figure 6(c) and this ranged from <20 $t\,ha^{-1}\,y^{-1}$ to >170 $t\,ha^{-1}\,y^{-1}$. The highest rates of $F+H$ occurred in low SQ fields, marginal lands, and subsoil exposed soils having low soil resistance to detaching forces. The lowest was observed in forest land, protected plantation areas, and farm lands with high soil quality regardless of the slope steepness. This study generalized that the rate of soil loss increased with an increase of detaching forces. It was observed from the field that the process of erosion can continue until first the topsoil and finally the subsoil disappear unless suitable controlling measures are implemented. However, it is a matter of fact that all soils detached cannot be reached at the outlet of the catchment because of deposition areas on the way to the outlet. It is therefore important to have information that shows the spatial distribution of soil transport capacity of the overland flow (TC) in the study catchment.

The spatial distribution of TC (Figure 6(d)) indicated higher values (>42 $t\,ha^{-1}\,y^{-1}$) on steep slope, marginal and over grazed lands, and sites with bare soils and intensively cultivated without proper soil management and conservation measures, whereas it indicated lower values (<5 $t\,ha^{-1}\,y^{-1}$) from relatively less disturbed areas (better vegetation and management practices). This indicated that TC is influenced not only by slope but also by cover crop, supporting practices, and soil erodibility and erosivity conditions. These could be the factors that led to the irregular spatial distribution and variability of the soil loss as TC which was estimated by MMF model.

In general, the TC value was lower than that of $F+H$ which attributed to the transport of fewer amounts of detached soils by rainfall drop and runoff impacts. Thus, erosion is transport limited in the study catchment. However, there were conditions whereby TC could be larger than $F+H$, for example, steep areas, compact soils, marginal lands, and farmlands with poor SQ. This could be related to the fact that in steep slope land, the possibility of deposition to take place in the natural flow is low and the time for soil infiltration is also short. The mean and spatial distribution of total soil detachment ($F+H$) was higher than the TC, indicating that the value of TC is taken to show the magnitude of annual soil loss from the study catchment. Thus, considering the TC values, the higher erosion risk areas can be identified scattered throughout the catchment. The model generally predicted erosion being limited by transportation, indicating that the amount of soil detachment is very high in the study catchment. This indicated that soil cover is too poor in which soil is exposed to detaching forces and also, the steep slope which generate high runoff can detach and transport large mass of soils.

3.3. Results of MMF Model Related to Reservoir Sediment Survey and Soil Profile Data. The model estimated soil loss at catchment level was compared with the survey based measured sediment yield from the reservoir located at the outlet of the catchment. The average catchment level soil loss (TC) estimated by MMF model was 26 $t\,ha^{-1}\,y^{-1}$ whereas the sediment yield measured from the reservoir survey was 20 $t\,ha^{-1}\,y^{-1}$. This resulted in percent difference (D) value of 30%. The similarity between the measured and model simulated value at catchment level was 70%, which is moderately acceptable. The MMF model seems to be overestimating the average soil loss (TC) from the entire catchment as compared to the sediment yield measured from reservoir survey, indicating that the model can pronounce erosion processes observed in the catchment using some extremely higher values of soil loss rate.

In addition, the soil erosion rate predicted by the model was compared with observed soil profile depth data in selected sites of the study catchment. The MMF model was assessed in terms of its capacity to identify areas of soil truncation and/or to predict lower erosion on areas where buried soils and/or alluvial/colluvial deposits or stable soils were observed. The MMF model accurately predicted erosion in about 80% of the pits observed in the catchment whereas the 20% disagreement was located at the upslope position of the catchment where the model predicted slight erosion for sites of a very truncated soil profile. In most sites (80%) of the catchment that characterized by truncated soil profile the model estimated high soil loss rate (>20 $t\,ha^{-1}\,y^{-1}$).

3.4. MMF Model Evaluation in relation to Other Studies (Models). For most of the catchment (>80%), the MMF model predicted higher soil loss rates than the maximum tolerable soil loss rate of 18 $t\,ha^{-1}\,y^{-1}$ estimated for the country [11]. This could be related to the reason that the study catchment could be characterized by very low soil infiltration, low soil water holding capacity and poor vegetation cover (inappropriate land use system), and low conservation measures. Consistent with this finding and explanation many previous reports indicated that a higher soil loss rate is strongly associated with high runoff resulting from absence of runoff flow obstacles such as vegetation cover, conservation measures, impoundments, and soil with low infiltration rate and low soil water holding capacity [54–60]. If an average annual soil generation rate of 6 $t\,ha^{-1}\,y^{-1}$ [61] is considered, the soil loss rates estimated by the model in most parts of the catchment could be beyond this acceptable level. It was less than 1% of the catchment area that experienced a soil erosion rate below 6 $t\,ha^{-1}\,y^{-1}$.

This study showed lower sediment yield (26 $t\,ha^{-1}\,y^{-1}$) as compared to a previous study using Soil and Water Analysis Tool (SWAT) model simulated result (30 $t\,ha^{-1}\,y^{-1}$) in the same catchment [31]. However, such differences can be attributed to model variability in the scale of data requirement. In addition, SWAT model is a continuous and long-time simulation model that might not be represented by the existing land use which can increase model prediction uncertainty [31]. Generally, the variability in soil loss predicted by both models is not higher than 15%, which is an acceptable model uncertainty. Sediment yield of 21 $t\,ha^{-1}\,y^{-1}$ based on an in-filled dam with a catchment area of 6.7 km^2 in one of the Tekezze River's tributaries in the Tigray region is also reported by Machado et al. [62].

In addition, a previous study using four catchments in the Tigray region reported an average soil erosion rate of 24 $t\,ha^{-1}\,y^{-1}$ [7]. In general, this and the above results are consistent with the trend of erosion estimated using MMF model in this study. Such comparison considers their similarity in the scale of measurement, input data requirement, and the farming system within the catchments. Therefore, the application of MMF model for estimating and identifying the severity of water erosion in order to introduce appropriate interventions is acceptable in conditions similar to the Mai-Negus catchment (study area).

4. Conclusion

This study concluded that GIS is a useful tool to integrate and manage spatially distributed hydrophysical data while assessing the spatial distribution of erosion. In this study, the MMF model results showed a lower rate of erosion for the soil transport capacity of overland flow (TC) when compared to the rate of soil detachment. This indicated that erosion is transport limited, and thus TC can show a realistic image of soil erosion hotspot sites in the study catchment conditions while introducing suitable soil conservation and/or management practices. Availability of such a study can help in making a quick assessment of runoff and soil loss status for the process of appropriate decision making. The average catchment level soil erosion rate (TC) estimated by MMF model was 26 $t\,ha^{-1}\,y^{-1}$ but there were sites with erosion rates higher than 42 $t\,ha^{-1}\,y^{-1}$. The sources of such higher soil loss rates were identified mainly to be the eroded sites, low soil quality soils, marginal land, overgrazed lands, and mono-cropping cultivated land system with poor soil management and conservation measures located in the mountainous (north-west) and central-ridge landforms of the study catchment. Therefore, introducing appropriate site specific interventions such as agroforestry, agronomic practices, exclosure of degraded lands, conservation measures based on the model erosion maps produced for the study catchment are suggested to be a practical solution for attaining sustainable environmental management and production services. However, the high soil detachment rates that occurred in many fields of the study catchment as a result of differences in spatial distribution of soil erosion influencing factors should be considered while designing and promoting appropriate practices to improve and maintain soil and water resources.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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