Study of soil moisture in relation to soil erosion in the proposed Tancítaro Geopark, Central Mexico:

A case of the Zacándaro sub-watershed

Jamali Hussein Mbwana Baruti

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by

Jamali Hussein Mbwana Baruti

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Degree Assessment Board

Dr. D. Rossiter	(Chairman) ESA Department, ITC
Dr. D. Karssenberg	(External examiner) University of Utrecht
Dr. D. P. Shrestha	(Supervisor) ESA Department, ITC
Dr. A. Farshad	(Co supervisor and students advisor) ESA Department, ITC
Dr. P. Van Dijk	(Programm Director, EREG), ITC

INTERNATIONAL INSTITUTE FOR GEO-INFORMATION SCIENCE AND EARTH OBSERVATION
ENSCHEDE, THE NETHERLANDS

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Abstract

A study on soil moisture in relation to soil erosion was conducted in the proposed Tancítaro Geopark, Central Mexico with special attention to the Zacándaro sub-watershed. The study aims at applying a simple water balance and an erosion model as conservation planning tools. Two methods i.e. Thornthwaite and Mather (1955) and the Revised Morgan-Morgan-Finney (2001) were applied in a GIS environment to model available soil moisture and soil loss rates. In addition, simple field tests were carried out to determine soil erosion hazards in the field.

Descriptive statistics as well as the Pearson's Product Moment Correlation were applied to analyse data. Sensitivity of model parameters namely rainfall amount, slope gradient and moisture storage capacity was carried out to evaluate the reliability of the RMMF model. In addition comparison of model results with data from a watershed close to the study area and evaluation of model results with erosion hazards classes determined using simple field tests as well as the results of the semi quantitative assessment of soil erosion features were carried out. Performance of the Thornthwaite and Mather model was evaluated by comparing model outputs with the sub-watershed annual stream flow data.

Results show that the average annual soil moisture over the entire sub-watershed was 240 mm yr^{-1}. In terms of land use/cover types the average available soil moisture was 304 mm yr $^{-1}$ for open forest, 82 mm yr $^{-1}$ for bare soil, 292 mm yr $^{-1}$ for closed forest, 123 mm yr $^{-1}$ for annual crops, 201 mm yr $^{-1}$ for perennial crops, 114 mm yr $^{-1}$ for grassland and 100 mm yr $^{-1}$ for shrubs. The average soil loss rates over the entire sub-watershed were 22 t ha^{-1} yr^{-1} with soil loss rates varying both within and between land use types as well as position in the landscape. In terms of land use types the average soil loss rates were 1t ha yr^{-1}for closed forest, 1 t ha yr^{-1} for open forest, 18 t ha yr^{-1} for annual crops, 16 t ha yr^{-1} for perennial crops, 4 t ha yr^{-1} for grassland, <1 t ha yr^{-1} for shrubs and 122t ha yr^{-1} for bare soil. A modest coefficient of correlation of (r = –44) on pixel by pixel basis was obtained between the predicted soil loss rates and available soil moisture holding capacity indicating that the lower the soil moisture storage capacity the higher the soil erosion rate. There was a degree of similarities between erosion hazards classes determined using simple fields tests and erosion hazard classes determined using the RMMF.

This study shows that soil moisture and erosion can be used as conservation planning tools in the study area especially in identifying erosion prone areas in relation to hydrological conditions.

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Dedication

Dedicated

To

My parents Mzee Hussein Mbwana Baruti and Mwanahawa Hussein who laid the foundation of my education and who have always encouraged me to pursue great things in life.

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List of Abbreviations

AGNPS	Agricultural Non–Point Pollution Sources
ASTER	Advanced Space-born Thermal Emission Reflection Radiometer
AWHC	Available Water Holding Capacity
CREAMS	Chemical Runoff and Erosion from Agricultural Management Systems
DEM	Digital Elevation Model
FAO	Food and Agricultural Organization
FCC	False Colour Composite
GIS	Geographic Information System
GPS	Ground Positioning system
ILWIS	Integrated Land and Water Information System
INEGI	Instituto Nacional de Estadistica Geografia e Informatica
ISRIC	International Soil Reference and Information Centre
LandSat ETM	LandSat Enhanced Thematic Mapper
RMMF	Revised Morgan-Morgan -Finney
SMU	Soil Mapping Unit
STREAM	Spatial Tools for River basin, Environment and Analysis of Management options
SWIR	Short Wave Infra Red
UNESCO	United Nation Education and Science Commission
USLE	Universal Soil Loss Equation

1. Introduction

1.1. Background

Soil and water are most important gifts to human and the availability of these resources in a well-defined spatial and temporal proportion is crucial for economic development, environmental quality, social well being and their sustainability. Despite this fact, competition for use of these resources among different needs and ever increasing rates of land degradation is being reported in many parts of world. The overall effects of the earlier mentioned problems are the significant degradation of agricultural production as well as increase in magnitude and recurrence of climatic extremes (drought and floods) and the overall ecological imbalances.

One of the most destructive and insidious processes, steadily increasing as a result of anthropogenic activities is soil degradation (Lal, 1997; Landa et al., 1997). This has raised many concerns regarding the potentially damaging impacts in relation to the often weak and non-existent management initiatives (Millward and Mersey, 1999) Land conversion within the developing world is occurring at unprecedented rate (Millward and Mersey, 1999). Expansion of commercial as well subsistence farming in many parts of the world is contributing significantly to the ecological alteration especially in many tropical countries (Landa et al., 1997; Lubchenco, 1998)

According to FAO (1997) soil degradation is the result of one or more processes, which lessen the current and or potential capability of soil to produce goods and services. Similar definition is shared by Lal (1993) in which he defined soil degradation as the decline in the soils capacity to produce goods of values to humans. What is common to these definitions is that the overall capacity of soil to produce goods and service is greatly affected as result of degradation processes.

Soil erosion is one of the serious forms of land degradation in the world (Nanna, 1996; Sohan and Lal, 2001). The problem has far reaching economic, political, social and environmental implication due both on-site and off-site damages (Thampapillai and Anderson, 1994). Each year 75 billion tons of soil are removed due to erosion with most coming from agricultural land and around 20 million hectares of land are lost (Ananda and Herath, 2003). Soil erosion is very high in Asia, Africa and South America averaging 30-40 t ha^{-1} y^{-1} (Barrow, 1991). This has raised a worldwide concern over the ability of land to feed the ever increasing world population and therefore threatening household food security.

Apart from soil erosion, anthropogenic activities have in many parts of the world resulted to the disrupted hydrological balances. Vegetation changes, by grazing, burning, cropping, substitution of species and clearing, greatly affect amount of water, which enters or is retained in the soil and hence making it more susceptible to drought (Thornthwaite and Mather, 1955; Krysanova et al., 2000).

Designing of sound conservation measures for water, soil and vegetation requires accurate data on degradation rates, their spatial extents, vulnerable areas, current sources, relative contributions from different sources and likely effects on land use (Meijerink and Lieshout, 1996). Traditionally soil erosion assessment has been centred on quantifying soil erosion from experimental plots (Harmsen, 1996). Though these methods provide the most accurate runoff and soil erosion, they have some practical limitation limiting their application. The identified deficiencies in soil erosion assessment methods are rectified in erosion models (Chisci and Morgan, 1988), although they also need data derived from plot experiments for calibration and validation. Soil erosion modelling has proved to be a sound approach to generate quantitative data that are necessary for designing of sound conservation measures (Shigeo et al., 1998; Millward and Mersey, 1999). Models are effective predictive tools of soil loss (Nearing et al., 1994; Yazidhi, 2003).

With the development of Geographic Information System (GIS) and remote sensing techniques, soil erosion modelling has now significantly improved (Shrestha, 2000). According to Wolfgang et al. (2002), remote sensing complemented with field ground truthing and GIS provide the best methodological toolset to investigate soil erosion. Remote sensing techniques are effective tools in providing input data in erosion modelling, and also are able to provide model parameters in spatial scale.

Increasing water demand for both domestic and agricultural purposes, expansion and intensification of traditional agriculture and deforestation in the proposed Tancítaro Geopark, Central Mexico are now exerting pressure on natural resources posing a challenge on how the available resources can be used in a sustainable way.

The present study was carried out to analyse the applicability of simple water balance and erosion models in a GIS environment as conservation planning tools to contribute to the sustainable management of the park.

1.2. Problem statement and justification

Deforestation activities, to acquire land for cultivation, are the major anthropogenic causes of land degradation with a strong impact on natural resources in Mexico (Santana, et al., 1989; Guzman and Iltis, 1997; Landa et al., 1997; Tapia-Vargas et. al., 2001). It has been reported that, Mexico has reduced after 1960 its temperate and tropical forests by 30 and 75% respectively (Tapia-Vargas et al., 2001), and by 1994, Mexico ranked third among the countries with the highest annual rates of deforestation (World Resources Institute, 1994). According to Veihe et al. (2001) 85% of the total land area in Mexico is affected by one form of land degradation and there has been an increase in the percentage of areas serious affected by soil erosion over the last decade.

The study area is within the protected Geopark. The thrust behind the Geopark concept lies on the promotion and enhancement of geologic heritage of the Earth and endorsement of geo-scientific disciplines (UNESCO, 1999). According to UNESCO (1999) for an area to be designated as a Geopark it has to meet a set of criteria one of them being evidences of sustainable practices for conservation and management. However, there are evidences that the long-term sustainability in the use of park resources is being threatened.

In the past three decades, significant resource degradation has been noted within and outside the park. Deforestation for both commercial and subsistence farming and for timber and other forest products collection is resulting in increased soil erosion and destructed hydrological balance. These phenomena are seriously threatening the long-term sustainability in terms of socio-economic and ecological functions obtained from the area.

These unfavourable trends call for well-focused interventions. Design of sound conservation measures for water and soil requires accurate data on relative degradation rates, spatial extents, vulnerable areas, relative contributions from different sources and likely effects on land use (Meijerink and Lieshout, 1996). Unfortunately in the study area such quantitative data necessary for designing sound conservation measures are lacking. Mexico, like many tropical countries, suffers from lack of financial resources for research, monitoring sources and outcomes of environmental degradation (Millward and Mersey, 1999). In order to maximize the allocation of scarce resources it is crucial to identify, prioritise and prevent other forms of degradation before they reach a stage that is irreversible or very expensive to repair (Wessels, et. al., 2001).

It is from the above arguments that the present study was carried out to study the applicability of simple water balance model and erosion modelling as conservation planning tools in the proposed Tancítaro Geopark.

1.3. Objectives

The overall objective of the research is to study the applicability of simple water balance and soil erosion models as conservation planning tools in the proposed Tancítaro Geopark focusing the Zacándaro sub-watershed in a GIS environment and therefore provide inputs to sustainable management of soil and water resources. Specific objectives were: -

- To determine the rates of water erosion and their spatial distribution in the proposed Tancítaro Geopark using a RMMF model (Morgan, 2001).
- To use simple field tests to determine soil erosion hazards.
- To study the relationship between soil erosion rates predicted using RMMF model (Morgan, 2001) and erosion hazards predicted by simple field tests.
- To determine the annual and monthly soil moisture storage capacities in the study area using simple water balance model and relate them to soil erosion rates.
- To establish the relationship between spatial distribution of vegetation and soil hydrological properties.

1.4. Research questions

- "What are the soil erosion rates in the study area with respect to land use/land cover and landscape position?"
- "Can the RMMF model adequately predict the soil loss rates with Andosols being the major soil type?"
- "Can simple field tests be used to determine soil erosion hazards in the study area?"
- "What is the relationship between erodibility hazard classes determined by simple field tests and erosion rates predicted using the RMMF model?"
- "What are the annual and monthly soil moisture storage capacities in the study area and their relationships to the predicted soil erosion rates?"
- "How does the combination of vegetation and soil affect soil hydrological properties?"

1.5. Hypotheses

- Soil erosion rates and their spatial distribution in the proposed Tancítaro Geopark are related to land use/land cover and position in the landscape
- Erosion modelling can adequately predict soil loss rates in the study area including the Andosols as major soil types.
- It is possible to determine soil erosion hazard classes in soils of the study area using the simple field tests.
- There is a relationship between soils erosion hazard classes determined by simple field tests and soils erosion rates predicted using the RMMF model
- There is a relationship between the predicted soil erosion rates to soil moisture storage capacities in the soils of the study area i.e. the higher the soil moisture storage capacity the lower the soil erosion.
- Specific combination of soil and vegetation affects the hydrological dynamics in the study area.

2. Literature Review

Soil erosion is one of the serious forms of land degradation in the world. Several factors interact to influence soil erosion at any given location. These factors include climate, topography, vegetation and management practices. Inherent soil properties such as texture, organic matter content, structure and permeability have been reported as the major factors that effect soil erodibility. In addition to these factors, the limited soil moisture storage capacity of the profile as well soil moisture content before rainfall is also considered as possible causes of soil erosion through its influence on overland flow production.

2.1. General overview of soil erosion and soil water modeling

Modelling of soil erosion and soil water involves a complex interaction of environmental processes. According to Thornthwaite and Mather (1957), changes of vegetation by grazing, burning, cropping, substitution of species and clearing can have greater influence on the amount of water that enters or retained by soil. Elimination of transpiration by stopping plant growth will always results in making more water available for soil moisture storage or for runoff. Depending on the nature of the surface cover, water that enters the soil or runs off the surface could result in soil losses. In their study to assess soil moisture deficit and potential soil loss in Elbe drainage basin, Krysanova et al. (2000) have reported a close linkage between potential erosion and soil moisture deficit. Figure 2.1 shows an interaction of environmental processes involved in the assessment of soil erosion and soil water modelling.

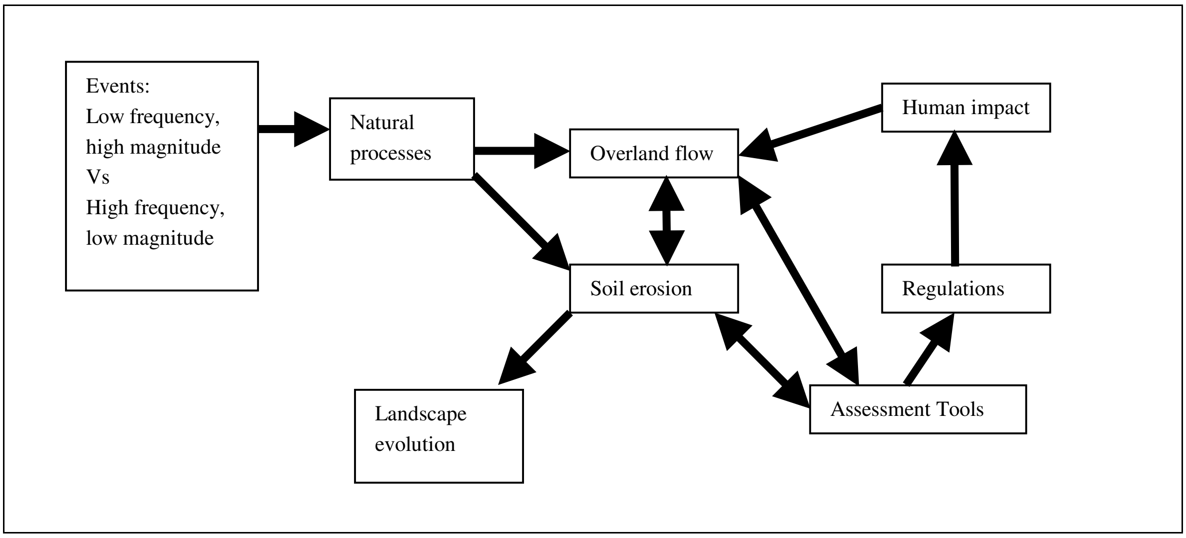


Figure 2-1 Environmental processes involved in soil erosion and water balance modelling (Source: Asmamaw, 2003)

2.2. Soil water

2.2.1. Available water capacity: Concepts and definitions

The dynamics of soil moisture represent a component of the overall water balance, and may be regarded as the single most important variable defining the fresh water availability (Krysanova et al., 2000). Soil moisture plays a critical role in crop growth and vegetation restoration in semi arid environment, and is also an important factor in hydrological modelling (Fu et. al., 2003).

Available water capacity (AWC) is the amount of water that the soil can store. It is the amount of water that is available for use by plants and is normally expressed as volume fractions or percentage (Booker Tropical Soil Manual, 1991). The soil moisture available to vegetation is the portion of soil moisture that is held between filed capacity and wilting point and hence soils with large differences between field capacity and wilting point generally favour plant growth. Dunne and Leopold (1978) have given water-holding properties of various soils on the basis of their texture (Figure 2-2). American Society of Civil Engineers (1990) gave amount of water held at different suctions for different soil textural classes (Table 2-1).

However some species of vegetation can have different rooting depth on different soil types and hence rooting depth of the vegetation besides soil types also determines water storage capacity (Table 2-2). The available water capacity as affected by rooting depth has been referred to as "*plant extractable water capacity*" (Dunne and Willmott, 1996). Similarly Reed et al. (1998), have referred it to as "*available water-holding capacity*".

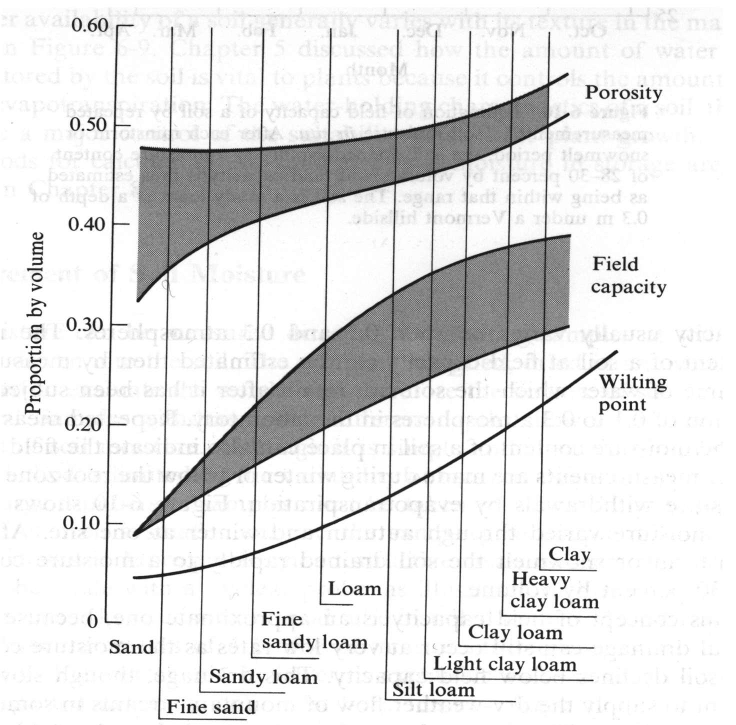


Figure 2-2 **Water holding properties of various soils on the basis of their texture** (Source: Dunne and Leopold, 1978).

Table 2-1 Typical values for soil-water parameters by texture

Texture Class	Field Capacity	Wilting Point	Available Capacity
Sand	0.12	0.04	0.08
Loamy sand	0.14	0.06	0.08
Sandy Loam	0.23	0.10	0.13
Loam	0.26	0.12	0.14
Silt Loam	0.30	0.15	0.15
Silt	0.32	0.15	0.17
Silt Clay Loam	0.34	0.19	0.15
Silty Clay	0.36	0.21	0.15
Clay	0.36	0.21	0.15

(Source: American Society of Civil Engineers, 1990)

Table 2-2 Suggested available water capacities for combination of soil texture and vegetation

Vegetation	Soil texture	Available water capacity (%volume)	Rooting depth (m)	Available water cap. of root- zone (mm)
Shallow rooted crops (spinach, peas, beans, beets, carrots. etc)	Fine sand	10	0.5	50
	Fine sandy loam	15	0.5	75
	Silt loam	20	0.62	125
	Clay loam	25	0.40	100
	Clay	30	0.25	75
Moderately rooted crops (corn, cereals, cotton, tobacco)	Fine sand	10	0.75	75
	Fine sandy loam	15	1.00	150
	Silt loam	20	1.00	200
	Clay loam	25	0.80	200
	Clay	30	0.50	150
Deep rooted crops (Alfalfa, pasture grass, shrubs	Fine sand	10	1.00	100
	Fine sandy loam	15	1.00	150
	Silt loam	20	1.25	250
	Clay loam	25	1.00	250
	Clay	30	0.67	200
Orchards	Fine sand	10	1.50	150
	Fine sandy loam	15	1.67	250
	Silt loam	20	1.50	300
	Clay loam	25	1.00	250
	Clay	30	0.67	200
Mature forest	Fine sand	10	2.50	250
	Fine sandy loam	15	2.00	300
	Silt loam	20	2.00	400
	Clay loam	25	1.60	400
	Clay	30	1.17	350

(Source: Thornthwaite and Mather, 1955)

2.2.2. Factors controlling soil moisture

Many of the man's activities can influence in one way or another the soil moisture relationship. Many of these activities have resulted in the decrease of the amount of water, which a soil can hold and hence making it more susceptible to drought. Soil moisture can vary from one place to another depending on topography, soils (Krysanova et al., 2000), vegetation and land uses (Fu et. al., 2000). A better understanding of the soil moisture variability is important in improving the hydrological models (Grayson et al., 1992; Fu et al 2003) and land management in runoff and erosion control (Fitzjohn, et al., 1998).

A number of researchers have studied soil moisture variability in order to determine their significance in the ecosystem processes and predicting soil moisture in catchment or on large scale (Anderson and Kneale, 1980; Bárdossy and Lehmann, 1998; Fu, et al., 2003). However little attention has been paid to the influence of land use pattern on soil moisture. This may largely be attributed to the difficulties of evaluating the effects of land use and its pattern on soil moisture. It has been reported that differences in land uses that produce a change in the soil properties and evapotranspiration are likely to increase soil moisture variability across the landscape (Andrew et al., 1998). Soil texture is the main factor that controls soil moisture, but in semiarid areas, other factors, such as topography, vegetation and land use may have an influence (Grayson and Western, 1998)

Near surface soil moisture has a major control on hydrological processes at both storm event scale and in the long term (Grayson and Western, 1998). It influences the partitioning of precipitation into infiltration and runoff and is important in evapotranspiration because it controls water availability to plants and thus affects the portioning of latent and sensible heat. Methods for estimating areal average soil moisture at a range of scales are needed for a variety of application in hydrology. Grayson and Western (1998) described methods of estimating soil water content into three main groups; (i) measurements of soil moisture in the field, (ii) measurements using remote sensing techniques and (iii) estimation via simulation models. However, all of these methods have advantages and disadvantages associated with each method especially with estimation of areal average soil moisture over a large area.

2.3. Water balance models as tools for studying soil moisture

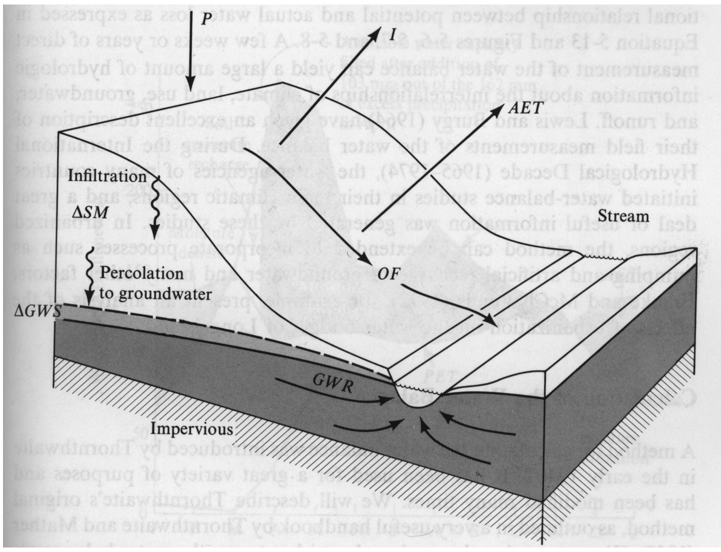
Where detailed data about soil layer, depth to ground water and vegetation are not available, hydrologists have often resorted to simple bucket models and budget schemes to model near surface hydrology (Reed et al., 1998). Despite numerous uncertainties associated with the simple soil water budget model, many researchers have applied this type of model to problems ranging from catchment scale studies to the global water balance and climate change scenarios (Thornthwaite and Mather, 1955; Manabe, 1969; Shiklomanov and Sokolov, 1983; Alley, 1984; Willmott et al., 1985; Mintz and Serafini, 1992, Mintz and Walker, 1993; Meijerink et al., 1994)

In recent years, the increasing imbalance between water supply and water demands has given rise to greater attention from both the relevant authorities and the general public on water resources planning program in which the long–term forecasting of water resources and its distribution has become one of the very important topics (Xiong and Guo, 1999). For the long-term forecasting of water resources distribution under different conditions, the monthly water balance models have been widely employed for the conversion of rainfall into runoff. According to Xiong and Guo (1999) the monthly water models are mainly applied in three fields i.e. reconstruction of hydrology of catchments, assessment of climatic change impact and evaluation of seasonal and geographical patterns of water supply and irrigation.

Until now, many different simple water balance models have been presented and many researches have been intensively conducted. Thornthwaite and Mather (1955) developed a set of deterministic monthly water balance models, in which only two parameters are used: the soil moisture capacity and the surplus water remaining fraction.

In the early 1990s water balance models were developed for studying the impact of climate change on the hydrology and water resources management (Mimikou et al., 1991; Vandawiele et al., 1992). Recently new water balance models have become much more complicated, by incorporating more information, to achieve more physical soundness and for more applications. However, the simple monthly water balance model can still be efficient and useful in terms of runoff simulations (Xiong and Guo, 1999). Ye et al. (1997) compared the performance of simple and complex models, and reported that a six parameter conceptual model did not yield inferior accuracy to complex model which uses twenty-two parameters. So, a simple model should be plausible, at lest in practical operation if it can give satisfactory results. Xiong and Guo (1999) have compared the results of two and five parameter water balance model and concluded that both of them gave almost similar results.

Water balance equations of Thornthwaite and Mather (1955, 1957) have been widely used in water balance studies either as an independent model (Meijerink et al., 1994) or as part of the physically based models as in the case of the STREAM model (Aerts et al., 1998). Figure 2-3 gives a schematic presentation of components of water balance on a hillside or a small catchment.



Legend
P=precipitation
I=interception
AET= actual evapotranspiration
OF= overland flow
ΔSM=change in soil moisture
ΔGWS=change in groundwater storage

Figure 2-3 **Components of the water balance on a hillside or small catchment**
(Source: Dunne and Leopold, 1978)

2.4. Soil erosion

2.4.1. Soil erosion and its factors

Soil erosion involves detachment, transport/redistribution and deposition of sediments (Lal, 2003). The slow geologic erosion is a constructive process, which has created vast tracts of fertile soils of alluvial flood plains and loess plateaus around the world. In contrast, the accelerated soil erosion, exacerbated by anthropogenic perturbations, is a destructive process. (Lal, 2003). It depletes soil fertility, degrades soil structure, reduces the effective rooting depth and destroys the most basic of all natural resources. Numerous, once-thriving civilizations have vanished because of the degradation of the resource base on which they arose (Brown, 1981). It is for these reasons the importance of protecting and restoring soil resources is increasingly being recognized by the world community (Lal, 2001).

Soil erosion is the result of interaction between rainfall as an erosive agent and soil as a medium that is detached and transported (Nanna, 1996). These processes are generally determined by locational factors including climate, soil, vegetation, man made soil conservation measures and topography (Petter, 1992; Morgan, 1995; Hudson, 1995; Nanna, 1996; Mkhonta, 2000,). In addition to biophysical factors, Kirkby et al. (2000) have indicated that social, economic and policy factors are important in determining the rate of soil erosion at any given time. It is clear that soil erosion is not only related to biophysical factors, but it has also a social, economic and policy dimensions. Figure 2-4 shows how different factors interact to influence soil erosion rates.

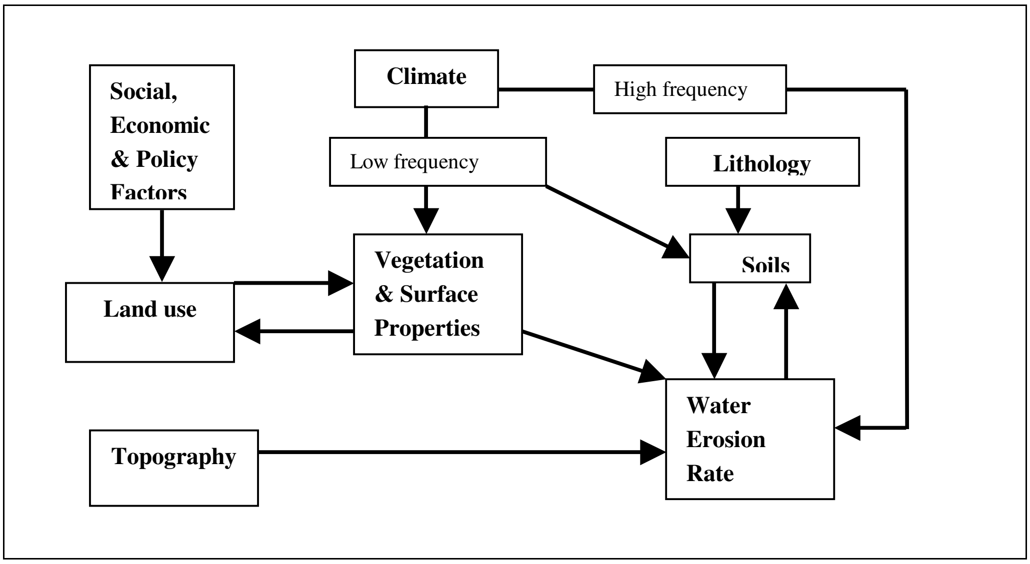


Figure 2-4 **Factors influencing water erosion rates** (Source: Kirkby et al., 2000)

2.5. Methods of water erosion assessment

Soil erosion rates vary widely over the landscapes, over a field and even along a slope profile within the field. In order to understand soil erosion over a particular area it is necessary to assess erosion at different landscapes for which various techniques are available. These techniques are briefly discussed in the following sections:

2.5.1. Soil loss assessment at plot scale

Traditionally soil erosion assessment has been centered on quantifying soil erosion from experimental plots and extrapolated to the wider landscape (Harmsen, 1996; Evans, 2002). However, many researchers have recently questioned the applicability of this approach over a wider landscape (Evans, 1993a; 1995a; Boardman, 1996; Herweg, 1996). While plot based approach can aid in understanding the processes and factors governing water erosion it is of little help in predicting soil loss rates in the landscape as a whole (Evans 2002). According to Evans (2002) and Bewket and Sterk (2003) the major draw back of plot experiment are particularly centered on the following aspects:

1. Runoff and soil carried in it are either collected by directing the flow of water over the lower edge of plot and so via a rapid fall in height in containers. Such a rapid increase in gradient provides a potent "driver" to the erosion system that would not usually be there in the field unless a ditch or stream was adjacent to the foot slope.
2. Plot level data indicate only the magnitude of soil loss at a particular area, without considering the influence of its surroundings.
3. Sediment deposition is almost completely excluded by the plot level measurements.
4. Generally speaking, extrapolating results obtained plot scale measurements to larger scales can be misleading because soil erosion is dependent on many factors such as variations in rainfall energy, gradient and length of slopes, inherent soil characteristics affecting erodibility, land use and land management practices.

Nearing et al. (1999) has also indicated that the variability in soil erosion is very large even among replicated plots, which is due to natural and measurement variability. Despite these set backs, it appears that plot scale measurement will remain to be important in understanding of processes and factors governing water erosion.

2.5.2. Rill erosion survey at field scale

Understanding the magnitude of soil loss at field scale offers a tool for practical conservation planning purposes (Bewket and Sterk, 2003). According to Herweg (1996) rill erosion survey can be defined as a semi quantitative method for assessing the extent of soil erosion damage under field condition, without involving expensive instrumentation. Herweg (1996) further mentioned that it is a more conservation–oriented method of soil erosion assessment than the plot and watershed level studies. According to Evans (1993a) field assessment of water erosion is based on two major assumptions.

1. Over the short term, splash and sheet wash are of minor importance in redistributing soil within a field other than over a distance of few meters.
2. After splash and sheet wash, it is rills and gullies that redistribute soil within a field or landscape.

Some researchers have also argued that good field surveys of erosion produces results fairly comparable with test plot derived data (Govers, 1991; Evans, 1993a). According to Herweg (1996), results from erosion survey are within 15 percent accuracy. Bewket and Sterk (2003) have concluded that being a semi-quantitative and qualitative assessment, survey results cannot be taken as accurate estimation of soil loss. But, low cost and the ease with which it can be applied under natural conditions at times compensate for the precisions and high cost test plot and watershed level studies.

2.5.3. Soil erosion assessment at watershed scale

This method involves determination of sediment yield at the outlet of the watershed. According to Evans (2002) assessment of soil erosion is preferably to be undertaken at a watershed level. Bewket and Sterk (2003) have argued that watershed level data are spatially aggregated, in the sense that only sediment yields at a point of outlet are measured and how much of it comes from which part of the watershed remains unknown. They further emphasized that watershed level do not indicate actual soil losses from cultivated fields which are the units of land use and management by farmers, to be readily used as inputs for planning of soil and water conservation.

2.5.4. Soil erosion assessment based on simple field test and erosion features of micro-topography

As an alternative to the expensive and time consuming traditional methods, simple field tests have been developed to estimate soil erodibility (Bergsma, 1990). The simple tests used in the assessment of soil erodibility in the field are crumb test, pinhole test, manipulation test, rainfall acceptance test, soil loss test, rilling test and shear vane test of the surface soil. According to Bergsma (1990), these field tests are considered to provide a good index of the aspect of erodibility and are meant to be used in surveys of soil erodibility and soil erosion hazards.

On the other hand, recording of erosion features of micro-topography is a method that has been developed to evaluate the erosion hazards directly in the field on the basis of the effect that erosion has left in a rainy period up to the moment of observation (Bergsma, 1992, 1997). Micro-topographic features being recorded include, original/resistant clods, eroded parts, flow surfaces, pre-rills, rills, depressions and vegetative matter.

2.6. Soil erosion modeling

2.6.1. Types of soil erosion models

A model represents an object or phenomenon that exists in the real world. A model is a simplification of processes and their interactions with the aim of extracting, evaluating and simulating the relevant processes (Renschler, 1996). A good model is the simplest one that correctly and consistently predicts the behaviour of the real world for the phenomena of interest (Aronof, 1989). With a need to generate quantitative data for planning of sound management of soil resources, erosion models are currently the most feasible and practical approach in generating data on erosion hazards (Meijerink and Lieshout, 1996).

Models are implemented through mathematical equations in a simplified form, however the reality can differ from model predictions (Nanna, 1996). These differences may be attributed to the way with which the phenomenon is represented as well as the spatial and temporal scales of the model. Several models have been developed and many new ones are in the process of being developed (Yazidhi, 2003). These models differ in terms of complexity, processes considered, and data required for model calibration and model use. In general there is no “best” model for all applications.

Merrit et al. (2003) have given some factors that affect the choice of a model for application which include (a) data requirements of the model, (b) model capabilities, (c) objectives of model user(s), (d) hardware requirements and (e) the accuracy and validity of the models including its underlying assumptions. Models fall into three main categories, depending on the physical processes simulated by the model, the model algorithms describing these processes and the data dependence of the model.

These main categories are empirical or statistical, conceptual and physical based model. Roo (1993) describes stochastic and deterministic models as a distinct class apart from those already mentioned. Despite these categories, the distinction between models is not sharp and therefore can be somewhat subjective and some models are likely to contain a mixture of each of these categories and hence a hybrid model. A brief description of model types is given bellow.

Empirical models: These are generally the simplest of all of the three model types. They are based primarily on the analysis of observations and seek to characterize response from these data (Wheater et al., 1993) and are generally based on the assumption of stationarity (Merrit et al. 2003). The computational and data requirements for such models are usually less than for conceptual and physical based models, often being capable of being supported by course measurements (Merrit et al., 2003).
Empirical models are frequently used in preference to more complex models as they can be implemented in a situation with limited data and parameters input (Merrit et al., 2003). Most models used in soil erosion studies are empirical models with USLE and its modifications being the widely used ones (Yazidhi, 2003)

Conceptual models: Conceptual models are typically based on the representation of catchment as a series of internal storages (Merit et al., 2003). According to Sorooshian (1991), conceptual models tend to include a general description of catchment processes, without including the specific details of process interactions, which would require detailed catchment information. This allows these models to provide an indication of the qualitative and quantitative effects of land use changes, without requiring large amount of spatially and temporally distributed input data (Merrit et al. 2003). Traditionally, conceptual models lump representative processes over the scale at which outputs are simulated (Whether et al., 1993). Recently developed conceptual models have provided outputs in a spatially distributed manner (Merrit, et al 2003).

According to Beck (1987), the conceptual models play an intermediary role between empirical and physical based models. Whilst they tend to be aggregated they still reflect the hypotheses about the process governing system behaviour. This is the main feature that distinguishes conceptual model from empirical models.

Physical-based models: These are models based on the knowledge of the fundamental erosion processes and incorporate the law of conservation of mass and energy (Bennett, 1974; Petter, 1992). In theory, the parameters used in physical-based models are measurable and so are known (Merrit et al., 2003). In practice, the large number of parameters involved and the heterogeneity of important characteristics, particularly in catchments, means that these parameters must often be calibrated against observed data (Beck et al., 1995; Wheater et al., 1993). Examples of physically based models include WEPP and AGNPS.

Stochastic and deterministic models: According to Roo (1993), Stochastic models are models in which any of the variables included in the model are regarded as random variables having distributions and probability, in contrary if all variables are free from random variation the model is regarded as deterministic.

2.6.2. Validation of soil erosion models

Model validation involves a procedure to determine how best the model predicts soil loss rates in the real world. Traditionally validation of soil erosion models has been implemented through the comparison of model output and measured values from experimental plots (Nearing, 1998). However, Poesen et al. (1996) have argued that to validate any model, unless that model only claims to predict plot or hill slope scale erosion rates, it needs to be tested against data collected in the field and not from plot experiments.

Another procedure used in model validation is the sensitivity analysis. According to Newham et al. (2003) sensitivity analyses are formalized procedures to identify the impact of changes in model input and components on model output. Sensitivity analysis is an important part of model validation indicating where model development and data gathering should be focused. Sensitivity analysis can help to answer the following types of questions:(a) does the model resemble the system or process under study? (b) which parameters, data inputs and model components exert a significant influence on the output variables and which are inconsequential? and, (c) do change in specific combinations of model parameters produce large influence on results i.e. are there significant interactions?

Campolongo et al. (2000), have identified three main settings where sensitivity analysis may be applied. These include: (a) factor screening to identify influential factors in a system with many factors, (b) local sensitivity employing partial derivatives to quantify the influence of model parameters, inputs and structural features for limited range of variations about specific operating points, and (c) global sensitivity analysis apportioning the output sensitivity to its causes, over the whole realistic operating range. According to McCuen and Synder (1983), determination of sensitivity of any parameters is given by sensitivity ratio determined by the output and input of a model in question.

2.7. The use of GIS and RS in soil erosion modelling

Soil erosion is spatial phenomena, thus geo-information techniques play an important role in erosion modelling (Yazidhi, 2003). While this is agreeable, the quality of the results matches the quality of the input data used (Svorin, 2003). Land use data required to run erosion model can be derived from remotely sensed data. In a GIS environment it is possible to link data generated from remote sensing with their spatial location (Mkhonta, 2000). In general the use of geo-information techniques offer the following advantages in erosion modelling: - (i) fast and cost effective estimates, (ii) possibilities to investigate larger areas, (iii) greater possibilities of continuous monitoring of these areas and (iv) possibilities to refine the soil erosion model depending on the required output scale i.e. rough global to more precise local scale. According to Yazidhi (2003), the use of digital elevation models and GIS offers possibilities to estimate more relevant topographical parameters that are useful in soil erosion modelling.

3. Materials, Methods and Techniques

3.1. Materials used

Materials used in the study included:

- Panchromatic aerial photographs at a scale of 1:75000 taken in April 1995 covering the study.
- LandSat ETM+7 with seven bands obtained in October 2000
- ASTER images obtained in October 2001 and March 2003
- Topographic map sheets at a scale of 1:50000 covering the study area (INEGI, 1995.
- Soil map at a scale of 1:50000 FAO/UNESCO system (INEGI, 1983).
- Digital land use/land cover map at a scale of 1:50000 (Fuentes, 2000).
- Geological map at a scale of 1:50000 (Mauro, 1996)
- Available digital cartography (contour lines, hydrological network etc.)
- Geomorphological map at a scale of 1:50000 (Fuentes, 2000).
- Technical reports on different themes within the study area.

Equipments used in the field included:

GPS receiver for geo-referencing, clinometer for slope measurements, pH meter, measuring tape for plant height measurements, soil auger, spade, field knife, altimeter, shear vane for cohesion measurements, core sampler for collection of samples for bulk density determinations, sampling bags. Munsell colour chart, soil description guidelines, FAO surface cover estimation charts, etc.

The software used for map processing was ILWIS®, MS® Excel for statistical analysis and MS® Word for word processing.

3.2. Methods and Techniques used

To attain, objectives of the study, methods and techniques used included the use simple water balance and erosion models to model soil erosion and soil moisture respectively. The annual runoff obtained from soil erosion modelling was used to calculate the runoff coefficient used in the soil moisture modelling while the potential evapotranspiration generated from the soil moisture modelling was used to parameterize the soil erosion model.

In an attempt to evaluate the performance of the model especially its ability to represents a real world, simple field tests, semi quantitative assessment of soil erosion features were also carried out. The general flow charts of techniques used is presented in Figure 3-1 while details of respective techniques are discussed in the subsequent sections

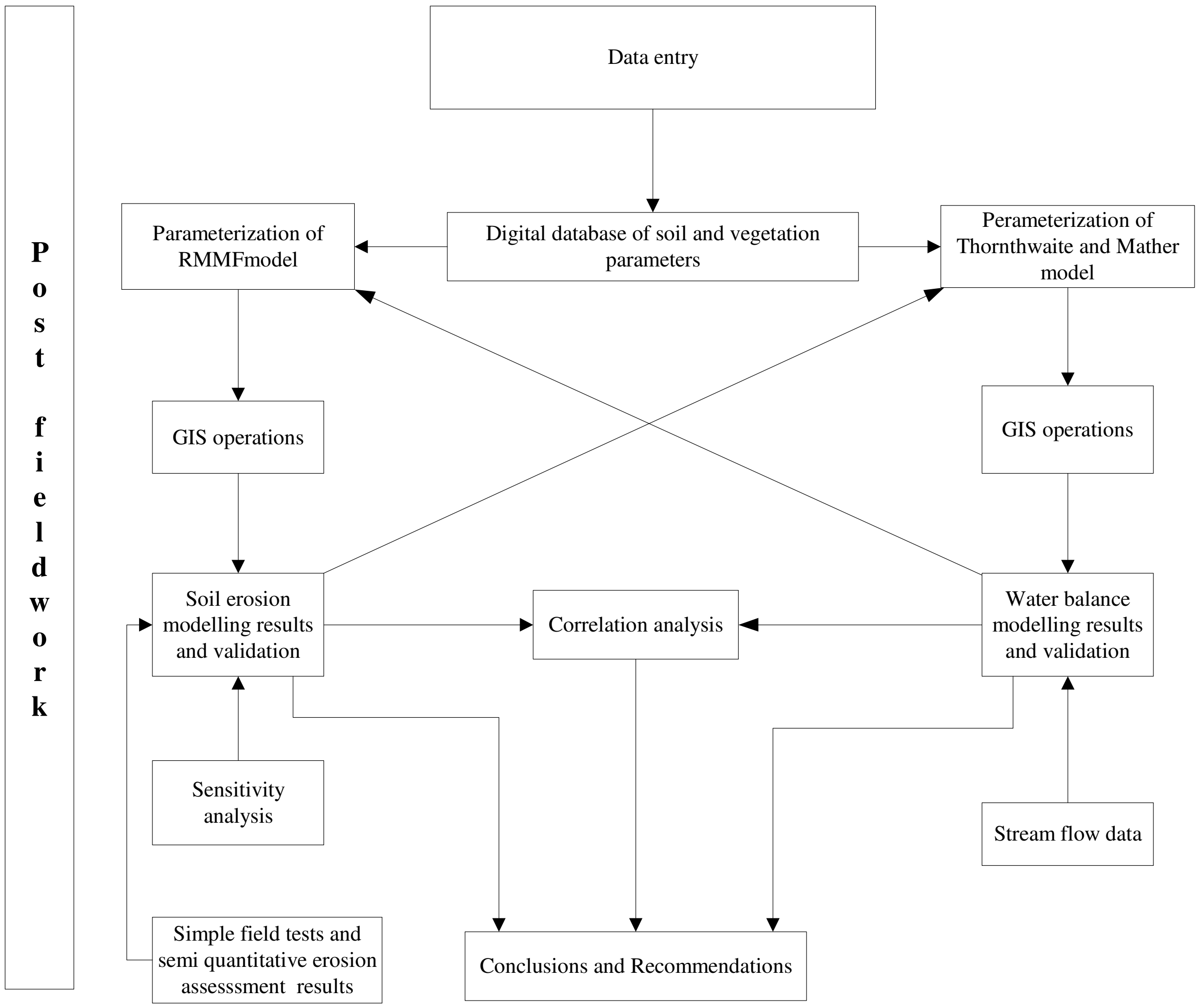


Figure 3-1 Flow chart of methods and techniques

3.2.1. Soil moisture modelling

In this study Thornthwaite and Mather (1955) model is selected to model soil water as a component of the water balance. The model is selected because of its simplicity, its ability to model soil water balance in an environment where data are limited common to many developing countries and compatibility with the GIS. Most of the data used in this model can be recorded using a standard meteorological station without requiring much sophisticated equipments.

The method uses long-term average monthly precipitation, long-term average monthly potential evapotranspiration and soil and vegetation combined characteristics to calculate water balance. Long-term average monthly evapotranspiration is estimated using long-term average monthly air temperature as an index of energy available for evapotranspiration, by assuming that air temperature is correlated to the integrated effects of net radiation and other controls of evapotranspiration, and the available energy is shared in fixed proportion between heating the atmosphere and evapotranspiration.

The empirical formula to estimate potential evapotranspiration developed by Thornthwaite and Mather (1957) has the following form:

$$PE = 16 * \left(\frac{10 * Tm}{H} \right)^{A}$$ **Equation 3-1**

Where PE = Potential Evapotranspiration in (mm/month)
A = Parameter obtained from empirical relation based on annual heat index
Tm = Mean monthly air temperature in (^{0}C), and
H = Annual heat index
Annual heat index is calculated as

$$H = \sum_{i=1}^{12} \left(\frac{Tmi}{5} \right)^{1.514}$$ **Equation 3-2**

and A is calculated as:

$$A = 0.49 + 0.01792 * H - 0.0000771 * H^{2} + 0.000000675 * H^{3}$$ **Equation 3-3**

The monthly potential evapotranspiration calculated in equation 3.1 is for standard month with thirty days and 360 hours of daylight. The standard potential evapotranspiration should be multiplied by appropriate factor to correct for number of days per month and the length of day. The correction factor is a function of latitude. Since study area is located approximately at 20^{0}N latitude, the correction is needed for each month.

The water balance model of Thornthwaite and Mather, is a two-dimensional model, it models the different water balance components for one point. Using GIS it is possible to model water balance in three dimensions, taking into account spatial distribution of rainfall, evapotranspiration and soil. In this way instead of calculating the water balance for one point, water balance can be calculated for every pixel of the entire catchment area. Meijerink et al. (1994) and Donker (1987) have explained water balance model of Thornthwaite and Mather and its use in GIS and accounting the spatial distribution of precipitation, evapotranspiration and soil.

Assuming that a certain fixed percentage $(C1)$ of the total rainfall will leave the area as surface runoff or direct storm runoff, the model is implemented as follows
Surface runoff (SR) is calculated as:

$$SR = C1 * Rain$$ **Equation 3-4**

Effective rainfall (P) is calculated as:

$$P = Rain - SR$$ **Equation 3-5**

From the total amount of effective rainfall that reaches the surface, evapotranspiration returns part to the atmosphere (ET). The remaining part, available for infiltration into the soil is surface recharge $(SRECH)$:

$$SRECH = (Rain - SR) - ET$$ **Equation 3-6**

or substituting (Rain-SR) with P in equation 3-6

$$SRECH = P - ET$$ **Equation 3-7**

When the soil is not yet at its water holding capacity (WHC) and $SRECH$ is positive (in other words: the effective rain is more than Evapotranspiration), $SRECH$ will be used to replenish the soil moisture (SM):

$$SM_i = SM_{i-1} + SRECH_i$$ **Equation 3-8**

Where: $i =$ month number

As soon as the soil moisture reaches WHC, the remaining part $(GRECH)$ will percolate to the groundwater:

$$GRECH_i = SRECH_i - (WHC - SM_{i-1})$$ **Equation 3-9**

When $SRECH$ is negative (in other words: the effective rainfall is less than evapotranspiration) water will be withdrawn from the soil moisture. The high atmospheric demand for water (ET) cannot be met by the effective rainfall. This is why additional water is withdrawn from the soil moisture. However, the soil moisture depletion curve is not linear but has an exponential shape; the drier the soil is, the more difficult it becomes to extract water. Therefore the actual evapotranspiration (AE) is less than ET. The soil moisture depletion curve is given by.

$$SM = WHC * EXP(-APWL / WHC)$$ **Equation 3-10**

Where: $APWL =$ accumulated potential water loss, a variable that describes the dryness of the soil in months with deficit of water $(SRECH < 0)$ the APWL is calculated as:

$$APWL_i = APWL_{i-1} - SRECH_i$$ **Equation 3-11**

(Note: $SRECH$ is negative in this case)

In months with surplus of water $(SRECH > 0)$ the APWL is zero.

When month $(i-1)$, with surplus of water, is followed by month (i) with a deficit, starting APWL value has to be calculated using the following formula:

$$APWL_{i-1} = -WHC * \ln\left(\frac{SM_{i-1}}{WHC}\right)$$ **Equation 3-12**

When $GRECH$ in month $(i) > 0$, water is added to the water still present in the ground water store $(DET(i-1)$. The ground water store acts as a buffer and causes a delay in the groundwater runoff. Therefore not all the water in the store will become part of the ground water flow. Only fixed fractions represented by C_2 will runoff in the same month, the rest is retained till next month as follows:

$$GRO_i = C_2 * (DET_{i-1} + GRECH_i)$$ **Equation 3-13**

Where $DET =$ Detention

The new detention value will be given by:

$$DET_i = (1 - C_2) * (DET_{i-1} + GRECH_i)$$ **Equation 3-14**

The direct storm runoff (SR) and the groundwater runoff (GRO) together will form the total predicted catchment outflow $(Tout)$ (both as surface and subsurface flow):

$$Tout = SR + GRO$$ **Equation 3-15**

By comparing this predicted total outflow with measured (observed) outflow, where available, an assessment can be made of water balance and its components.

Input parameters needed to run the Thornthwaite and Mather (1955) model are listed in Table 3-1 while the methodological flow chart indicating the steps followed in soil water modelling in shown in Figure 3-2

Table 3-1 Input parameters for the Thornthwaite and Mather model

Factor	Parameter	Definition and remarks
Climatic	P	Long term mean monthly rainfall (mm)
	T	Long term mean monthly temperature (^{0}C); used also to estimate potential evapotranspiration
	E_a	Actual evapotranspiration (mm); which is a function of land cover
	E_0	Potential evapotranspiration (mm); obtained from meteorological stations or estimated from the long term mean monthly temperature
Land use /land cover	Rooting depth	The depth with which plants can extract water
Soil	Soil profile information	Horizon depth and texture

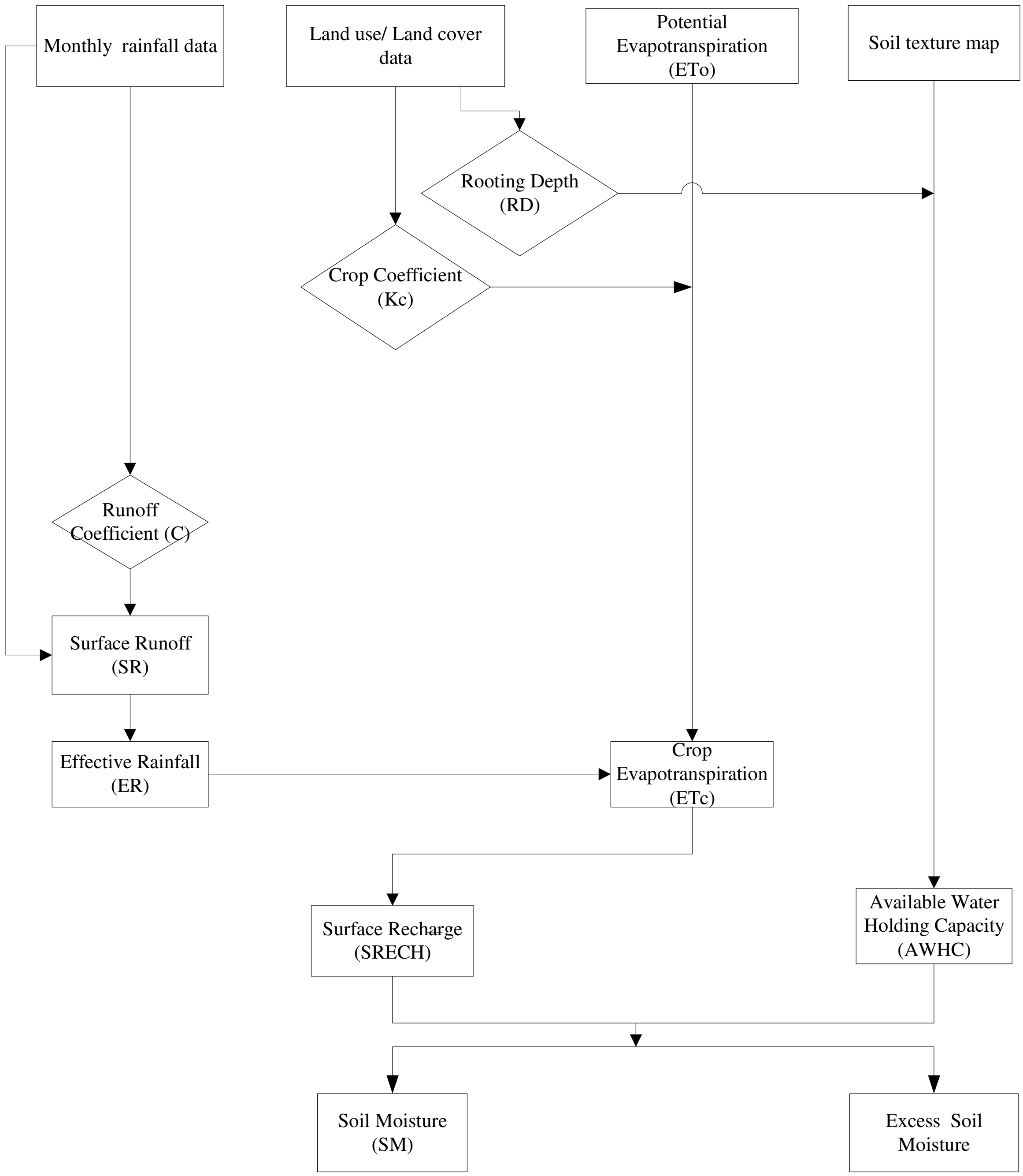


Figure 3-2 Methodological flow chart for the soil moisture modelling

3.2.2. Soil erosion modelling

Many soil erosion models exist within the scientific domain, however, the RMMF model (Morgan, 2001) was selected because of the following reasons (a) it can readily be implemented in a GIS environment, (b) model parameters are based on both empirical and physical processes and, (c) data requirements are not too complex or unattainable within a developing country.

The RMMF model is an empirical one for predicting annual soil loss from field-sized area on hill slope. The idea of developing this model was to bridge the gap between models such as USLE and CREAMS. It has a stronger physical base than USLE and more flexible than CREAMS. The model separates the soil erosion process into two phases i.e. the water phase and sediment phase. In the water phase annual rainfall is used to determine the energy of rainfall for splash detachment and the volume of runoff assuming that runoff occurs when the daily rainfall exceeds a critical value representing moisture storage capacity of the soil-crop complex and that daily rainfall amounts approximates an exponential frequency distribution. In the sediment phase, splash detachment is modelled using a power relationship with rainfall energy modified to allow for the rainfall interception effect of the crop. The model has been revised with new changes incorporated owing to increase in data availability and difficulties in estimating certain parameters. In the revised version, changes have been made to the way soil particles detachment by rain drop impact is simulated, which now takes into account of plant canopy height and leaf drainage, also soil particle detachment by flow has been added (Morgan, 2001).

The model uses a number of equations to estimate finally annual soil loss as follows:

Estimation of rainfall energy

The energy of rainfall is calculated by taking into account the way rainfall is partitioned during interception and the energy of the leaf drainage. The model takes the annual total rainfall $(R; mm)$ and computes the proportion that reaches the ground surface after allowing for rain interception $(A; 0-1)$. R and A are multiplied together to derive effective rainfall (ER) as follows.

$$ER = R * A$$ **Equation 3-16**

The model then distributes effective rainfall into rainfall that reaches the ground without interception, and rainfall that reaches later as leaf drainage (LD) after being intercepted by plant canopy $(CC;\%)$ using the following equation:

$$LD = ER * CC$$ **Equation 3-17**

Leaf drainage is then used to calculate direct throughfall (DT) as shown below:

$$DT = ER - LD$$ **Equation 3-18**

Kinetic energy is then calculated for effective rainfall of leaf drainage $(KE(LD); j/m^2)$ and effective rainfall of direct throughfall $(KE(DT); j/m^2)$. $KE(LD)$ and $KE(DT)$ are function of plant height (PH) and intensity (I) respectively. The Kinetic energy of direct throughfall is computed as follows.

$$KE(DT) = DT(11.87 + 8.73 \log_{10} I)$$ **Equation 3-19**

The Kinetic energy of leaf drainage is given by:

$$KE(LD) = (15.8 * PH^{0.5}) - 5.87$$ **Equation 3-20**

When equation 3-20 yields a negative value, the energy of the leaf drainage is assumed to be zero. $KE(LD)$ and $KE(DT)$ are added together to give the total energy of effective rainfall $(KE; j/m^2)$.

Estimation of runoff

Annual runoff (Q) is calculated using a relational equation using annual rainfall $(R; mm)$, mean rain per rain day $(R_0 : mm)$ and moisture storage capacity. Soil moisture storage capacity $(R_c; mm)$ is in turn a function of bulk density $(BD; mg/mg^3)$, soil moisture content at field capacity $(MS; \%ww)$, effective hydrological depth $(EHD; m)$, and ratio of actual to potential evapotranspiration (E_T / E_0). The following equation is used to compute soil moisture storage capacity:

$$R_c = 1000MS * BD * EHD * (E_T / E_0)$$ **Equation 3-21**

Mean rain days is calculated as follows:

$$R_0 = R / R_n$$ **Equation 3-22**

Where R_n: Number of rain days in a year.
From above equation the annual runoff is then given by:

$$Q = R * \exp(-R_c / R_0)$$ **Equation 3-23**

Estimation of soil particle detachment by raindrop

Soil particle detachment by raindrop impact $(F; kg/m^2)$ is calculated as a function of Kinetic energy $(KE; j/m^2)$ and soil erodibility $(K; g/j)$ as follows:

$$F = K * KE * 10^{-3}$$ **Equation 3-24**

Estimation of soil particle detachment by runoff

Computation of soil particle detachment by runoff $(F; kg/m^2)$ is calculated as a function of runoff $(Q; mm)$ slope steepness $(S;^0)$, soil resistance (Z) and ground cover $(GC; \%)$. Soil resistance is in turn dependent on surface cohesion $(COH; kpa)$. The model assumes that particle detachment by runoff only occur where soil is not protected by ground cover. Soil resistance is computed as follows:

$$Z = \frac{1}{(0.5COH)}$$ **Equation 3-25**

Soil detachment by runoff is then calculated as follows,

$$H = ZQ^{1.5} \sin S(1 - GC) * 10^{-3}$$ **Equation 3-26**

Total particles detachment $(D; Kg/m^2)$ is finally computed as a sum of soil particle detachment by runoff and soil particle detachment by raindrop impact as shown below.

$$D = F + H$$ **Equation 3-27**

Estimation of sediment transport capacity

Transport capacity of runoff $(TC; kg/m^2)$ is estimated as a function of runoff (Q) surface cover factor (C), and slope gradient $(S;^0)$ as follows:

$$TC = CQ^2 \sin S * 10^{-3}$$ **Equation 3-28**

Estimation of soil erosion

TC is compared with D and the lower of the two is taken as the annual soil loss (kg/m^2).

The input parameters needed to run the model are listed in Table 3-2, while the methodological flow chart in predicting soil loss using the RMMF model is given in Figure 3-3

Table 3-2 Input parameters for the revised MMF model

Factor	Parameter	Definition and remarks
Rainfall	R	Annual or mean annual rainfall (mm)
	R_n	Number of rain days per year
	I	Typical value for intensity of erosive rain (mm/h):
Soil	MS	Soil moisture content at field capacity or 1/3 bar tension (%w/w)
	BD	Bulk density of top soil layer (Mg/m^3)
	EHD	Effective hydrological depth of soil (m); will depend on vegetation crop cover, presence or absence of surface crust, presence of impermeable layer within 0.15 m of the surface
	K	Soil detachability index (g/j) defined as the weight of soil detached from the soil mass per unit of rainfall energy
	COH	Cohesion of the surface soil (kPa) as measured with a torvane under saturated conditions
Landform	S	Slope steepness (^{o})
Land cover	A	Proportion between (0 and 1) of the rainfall intercepted by vegetation or crop cover
	E_t/E_0	Ratio of actual (E_t) to potential (E_0) evapotranspiration
	C	Crop cover management factor; combines the C and P factors of the Universal Soil Loss Equation
	CC	Percentage canopy cover, expressed as a proportion between 0 and 1
	GC	Percentage ground cover, expressed as a proportion between 0 and 1
	PH	Plant height (m), representing the height from which raindrops fall from the crop or vegetation cover to the ground surface

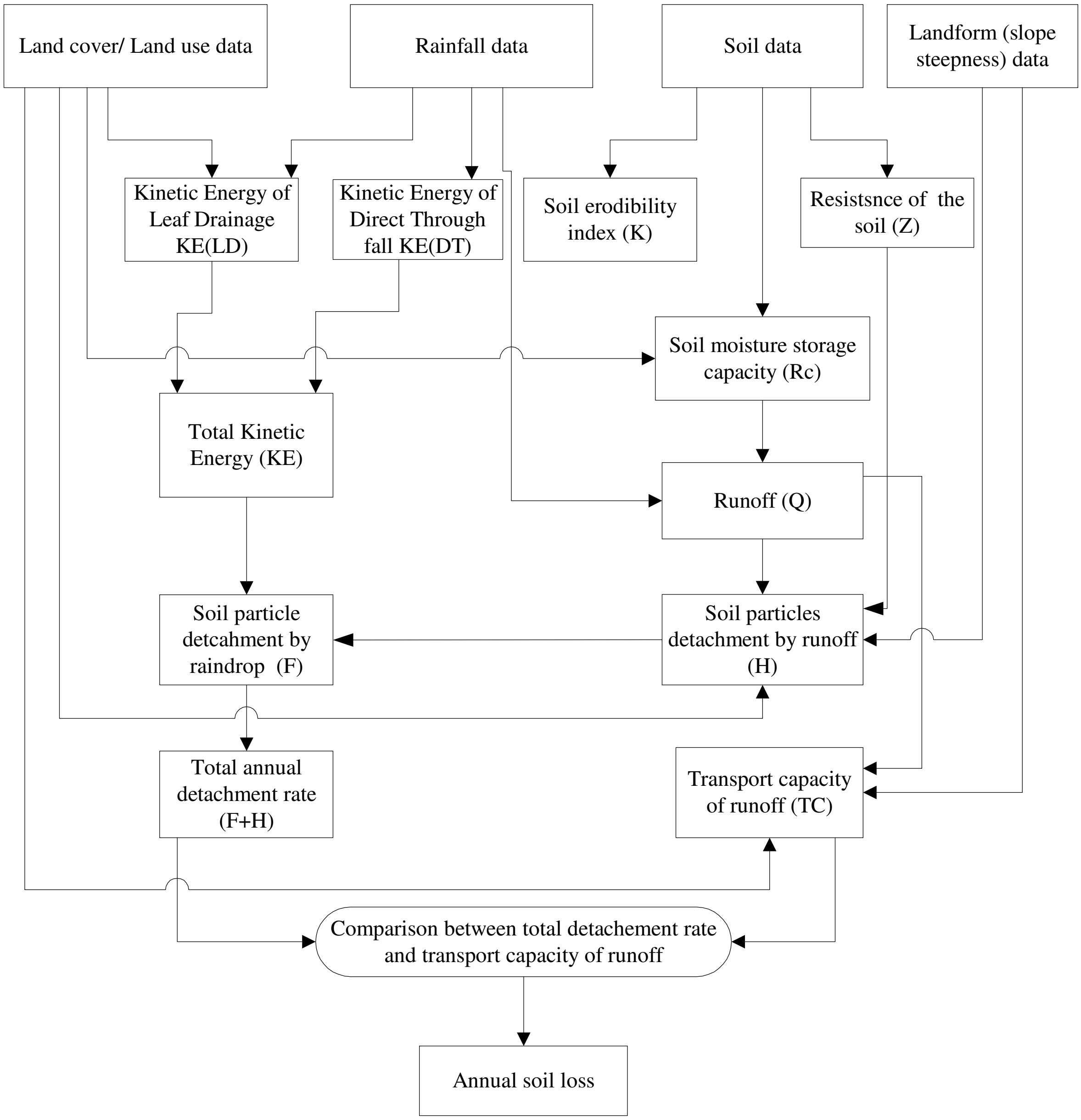


Figure 3-3 **Methodological flow chart for RMMF model**

3.2.3. Methods and techniques for simple field tests

In this study, soil erosion hazard was also assessed using simple field tests as described by Kunwar et al. (1999). The following methods were used in conducting simple field tests:

Assessment of soil erodibility

Soil erodibility is a measure of susceptibility of a given soil to erosion by rainfall and run off. In addition to other factors such as topographic position, slope steepness and amount of disturbance during tillage, soil properties are the most important determining factors for soil erodibility.

This approach is intended to evaluate the erosion hazard directly in the field. Different field tests were applied in the field, each of them analysing a specific component of the general soil erodibility. Each of these tests gives information about soil characteristics relevant for soil erodibility. To some degree the tests can predict the condition that lead to risk formation, being a processes largely determined by amount of overland flow, the steepness of the slope and properties of the material. Table 3-3 shows simple tests used and components of soil erodibility.

Table 3-3 Soil erodibility components and relevant soil characteristics

Erodible Soil Material	Overland flow production
1. Soil texture	1. Surface storage
2. Soil surface structure	2. Surface sealing
2.1 Structure grade	3. Infiltration (soil structure, especially macro pores
2.2 Structure size	4. Soil profile storage
3. Structural stability of soil surface	4.1 Macro porosity
4. Surface gravel	4.2 Permeable depth
ESP	4.3 Drainage condition
Content of electrolytes in runoff	

(Source: Kunwar et al., 1999)

From Table 3-3 it is evident that the availability of erodible material for transport by the overland flow depends on many soil characteristics. In determining the soil erosion hazard, it is important to note that soil erodibility alone is not enough to predict such a hazard, but together with vegetation cover and topography which are important determinants of soil erosion severity. The following simple field tests were carried out: (a) crumb test, (b) manipulation test, (c) rainfall infiltration test (rainfall acceptance), (d) pinhole test, and (e) shear vane (torvane) test of the surface soil. From these tests, information on the availability of material for erosion and overland flow production is obtained. Table 3-4 summarizes types of tests and component of erodibility determined by the test in question.

Table 3-4 Field tests and their soil erodibility components

Test	Erodibility component
1. Crumb Test	Detachment
2. Manipulation Test	Detachment
3. Rainfall Infiltration Test	Overland flow production
4. Pinhole Test	Resistance to Scour
5. Shear vane Test	Resistance to Scour

Crumb Test

This test shows rating of soil crumb behaviour when submerged in water. It is carried out to measure structure stability of the dry soil against wetting. It gives an idea about sensitivity to sealing by wetting of soil. The test is performed on three air-dry clods or aggregates of about 1 cm in diameter in 50 cc volume of water. The reaction of the clods (soil aggregates) after five minutes is observed and rated as follows:

Class 1: no change
Class 2: some collapse
Class 3: Some stable remnants (in the center)
Class 4: Complete collapse
Class 3 and 4 are checked by moving a needle of the pinhole test across the bottom of the beaker against the remains of the soil ball.

Manipulation Test

This test is particularly applied to determine the coherence of soil aggregates. The strength of expression of the topsoil structure, gives an indication of the availability of material for erosion. The test consists of manipulating a soil volume of about 2 cubic centimetres at plastic limit to make most complex forms out of series of defined forms. The results are observed and rated as shown in Table 3-5.

Table 3-5 Manipulation test

Forms	Classification of general textural class	Rating of detachability of erodible material
A simple mound	Sand	7
A tablet	Loamy sand	6
A roll of 10 cm with cracks	Sandy loam	5
A roll of 10 cm with no cracks	Loam	4
Horseshoe with cracks	Clay loam	3
Horseshoe without cracks	Loamy clay	2
A circle	Clay	1

Erodibility depends also on the amount of overland flow that is generated by the soil profile. It is therefore necessary to combine the detachability with the rain storage in the profile and the amount of overland flow production to arrive a value or class of soil erodibility.

Rainfall infiltration/ Acceptance Test

This test indicates the amount of rain, which does not take part in overland flow. It depends not only on infiltration but also on surface depression storage. Rainfall acceptance is used to calculate the amount of water that infiltrates in 1 hour, under splash and with only slight pounding. The artificial rain of about 24 mm in portion of about 4 mm is applied from 30 cm height using a plastic box with perforated lid, held upside down and pressed manually on its bottom side. Rain is resumed when 10 percent of the surface is still flooded. The rain falls inside a 10 cm diameter cylinder, about 15 cm high, pushed 2 cm deep into the soil. The time needed for infiltration of 24 mm is recorded.

Pinhole Test

The test is performed on a moulded ball of soil of about 3 cm diameter, at sticky point of wet consistency. A light concavity is made at one side where water will be entered through a narrow hole. A hole is made of 1 mm diameter by a small pin. The ball is washed of loose soil. About 50 cc clear water is poured using a funnel. Colouring of the water by dispersive clay in suspension is rated, and amount of erosion of the hole in the soil ball is judged after breaking the ball open. The results are rated as follows:
Class 1: clear water, no erosion of hole.
Class 2: some suspension, little erosion of hole.

Class 3: distinct suspension, distinct erosion of hole.
Class 4: muddy water, strong erosion in hole, may be collapse of soil ball.

Shear Vane Test

This test is used to measure the shear strength of saturated soil surface against the pressure of torvanes. A Torvane apparatus is used with vanes of 2 cm wide, and 4 cm long. The vanes are pushed into the soil for a depth of 1 cm. After turning the handle of the apparatus till the vanes break the soil because of increasing torsion, the final torsion is read on a scale that fixes the indication of the largest force used during the experiment. The readings are repeated ten times on the area of the micro plot and average of the ten readings taken as final result.

3.2.4. Semi-quantitative assessment of soil erosion features

As an aid to the validation of soil erosion model, a semi quantitative approach to assess erosion features as proposed by Barthes and Roose (2001), was performed in some representative sites. The procedure involved recording the frequency of each erosion feature in 10 m transect, perpendicular to slope and replicated three times. The frequencies of erosion were marked from 0 (absence) to 4 (omnipresence). These erosion features were sedimentation crust (a1), stones on the surface (a2), small pedestals (a3), microcliffs (a4) related to the sheet erosion. Other features related to the linear erosion included, grooves (b), rills (c), and gullies (d). Grooves, rills and gullies were defined by their depth, which was < 10, 10 – 30 and >30 cm, respectively.

Soil erosion index for each of the transects was then calculated using the following equation:

$$\textit{Erosion index} = a1 + a2 + a3 + a4 + 2b + 3c + 4d. \qquad \textbf{Equation 3-29}$$

3.3. Description of the study area

3.3.1. Location

The proposed Tancítaro Geopark is located in the central Mexico in Michoacán state and belongs to the Mexican Volcanic Transverse Belt. The area is located between the coordinates 19° 18' 26'' and 19° 33' 26'' North, and between 102° 11' 19'' and 102° 26' 13'' West. Zacándaro is one of the fourteen sub-watersheds proposed for Tancítaro Geopark. The total area of the proposed Tancítaro Geopark is approximately 720 km^2 while the Zacándaro sub-watershed covers an area of approximately 40 $km^{2.}$. The Zacándaro sub-watershed represents a manageable, naturally bounded land allocation, which can be considered to function as a self-contained system. The location of the study area is shown in Figure 3-4.

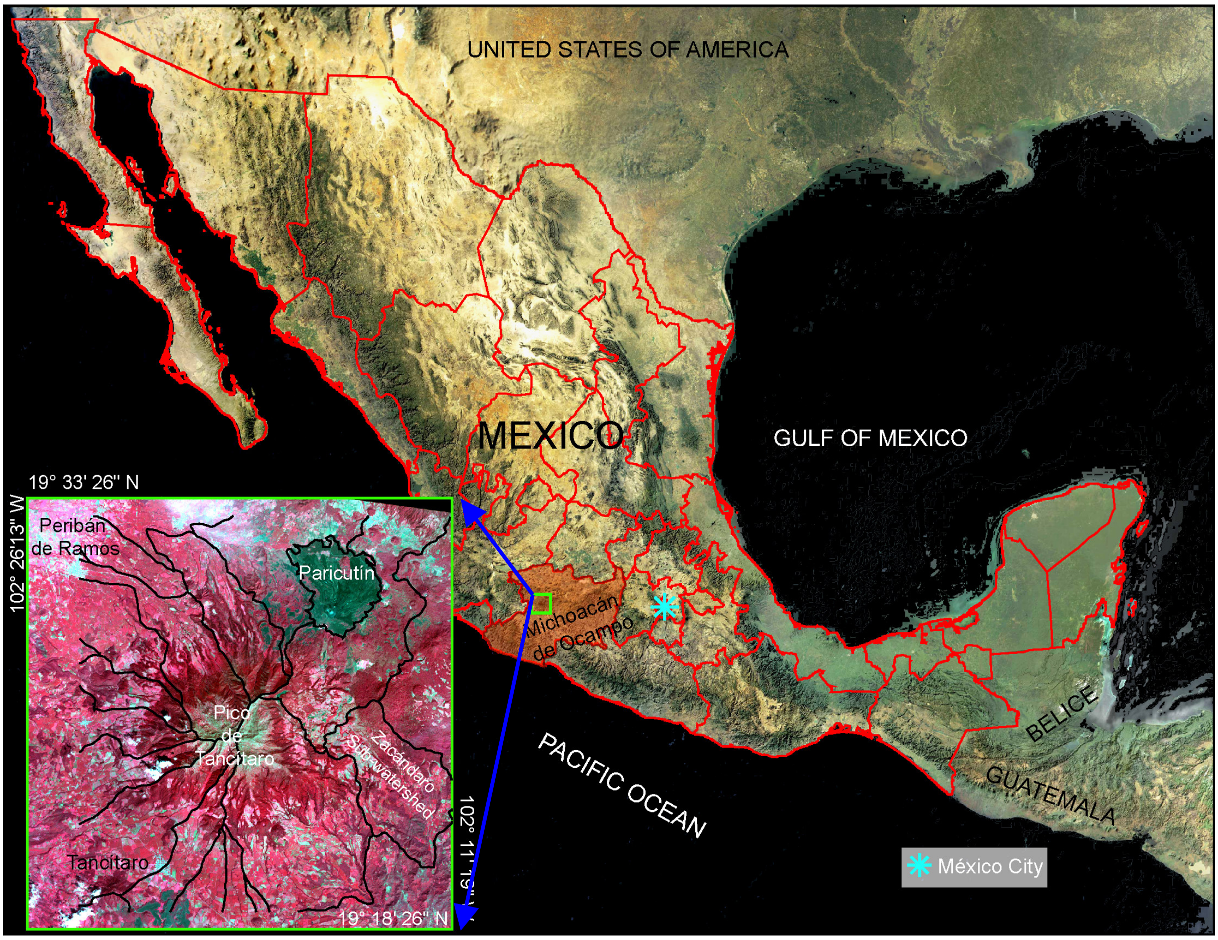


Figure 3-4 Location of the proposed Tancítaro Geopark

3.3.2. Topography

In general the Zacándaro sub-watershed is located in the region known as Mexican, Neo-volcanic Axis. The area is formed by a Plio-quaternary stratovolcano surrounded by a Holocene monogenetic volcanoes consisting mainly of ash cones and recent lava flows and lava mesas alternated with inter-mountainous valleys. The elevation in the area ranges between 1600 and 2900 m above sea level

3.3.3. Climate

The climate in the study area is highly influenced by elevation differences and seasonal variations. In the high altitudes, the climate is temperate while in low elevation the climate is more tropical. Rainfall occurs during May and October. Annual precipitation varies with altitude, which ranges between 800 mm to over 1500 mm. The number of rainy days in a year is also related to the elevation and they vary from 50 to 120 days. The dry period is November to April.

Mean monthly and annual temperatures vary with elevation. The mean annual temperature ranges between 8 and 28 ^{0}C. Data on humidity and evaporation covering the study area are not available. Based on the broad climate classification, the study area can be considered to fall within a tropical wet-dry climatic zone (Aw-Köppen climatic classification).

Tables 3-6 and 3-7 present precipitation and temperature data for thirteen stations located within and close to the study area, while Figures 3-5 and 3-6 show mean monthly precipitation and temperature over the entire catchment.

Table 3-6 Monthly rainfall data from thirteen stations

Station*	Jan.	Feb.	Mar	Apr	May	Jun	Jul	Aug.	Sep	Oct	Nov	Dec	Tot	Alt	Period
Apatzingan, CFE	21.6	1.6	0.7	0.7	21.0	134.2	178.8	167.6	186.1	81.7	28.8	13.5	836.0	320	1940-96
Charapendo,	27.4	16.1	5.4	8.9	36.8	192.9	281.3	229.5	239.7	96.5	75.9	19.7	1196.3	1000	1970-90
Jicalan, Uruapan	30.4	8.0	4.2	15.2	50.8	268.8	340.9	303.9	302.7	124.9	40.4	12.8	1502.8	1610	1964-96
Los Chorros del viral	21.1	6.4	2.2	3.2	47.0	173.7	204.6	166.1	200.0	83.1	29.8	9.1	946.2	1225	1966-93
Los Limones,	25.3	5.5	1.8	4.6	29.3	182.8	251.9	188.9	210.8	99.1	34.0	8.8	1042.7	1225	1955-96
Los Reyes,	14.3	5.2	2.3	1.9	32.8	166.8	183.5	180.8	161.2	80.9	21.9	9.2	860.9	1280	1945-85
Nueva Italia,	18.1	0.8	0.1	3.5	27.9	158.5	157.1	142.6	131.3	48.0	16.1	1.7	705.5	460	1957-96
Paracuaro, Paracuaro	10.5	1.3	1.6	4.2	26.8	182.4	226.1	223.1	209.0	97.1	18.5	2.6	1003.2	498	1970-95
Periban, Periban	19.3	6.2	4.2	1.3	29.1	207.4	306.3	272.3	242.9	119.2	38.8	8.5	1255.2	1630	1969-96
Punta de Agua	13.5	0.6	2.9	1.3	18.1	148.8	144.8	137.1	147.1	46.5	20.4	5.6	686.4	279	1970-85
Taretan	25.2	3.9	2.3	2.7	38.2	231.0	295.5	208.6	229.6	87.4	35.5	5.6	1165.7	1170	1958-96
Uruapan	40.3	12.4	7.9	12.8	46.0	271.5	346.3	340.6	321.7	138.2	32.1	15.3	1584.8	1610	1963-96
Tancítaro	19.0	4.4	2.4	4.0	29.1	167.8	206.5	181.8	184.2	78.0	25.6	7.9	910.5	3800	2002

Table 3-7 Mean monthly temperature from thirteen stations

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean	Alt	Period
Apatzingan, CFE	24.3	25.5	27.8	29.9	30.9	29.7	25.7	27.4	27.2	27.5	25.8	24.7	27.4	320	1940-96
Charapendo,	20.8	21.1	22.0	23.5	24.2	24.0	22.9	23.0	22.9	23.1	21.8	21.3	22.6	1000	1974-90
Jicalan, Uruapan	14.9	15.4	16.9	18.7	20.0	20.0	19.1	19.0	18.9	18.3	16.7	15.9	17.8	1610	1964-96
Los Chorros del viral	21.1	22.2	24.3	26.4	27.4	26.0	23.8	23.5	23.3	23.6	22.6	22.1	23.9	1225	1966-93
Los Limones,	17.9	18.7	20.4	22.4	23.7	23.2	21.5	21.4	21.3	21.2	19.7	18.9	20.9	1225	1955-96
Los Reyes	17.6	18.7	20.1	22.0	23.3	23.1	21.4	21.1	21.1	21.0	19.5	19.1	20.7	1280	1945-85
Nueva Italia,	24.7	25.5	26.4	27.3	28.2	27.3	26.6	26.5	26.2	26.3	25.8	25.2	26.3	460	1943-96
Paracuaro, Paracuaro	23.4	24.5	25.9	27.7	28.6	27.5	25.6	25.6	25.3	25.2	24.7	24.2	25.7	498	1974-89
Periban, Periban	17.5	18.1	19.8	21.4	22.2	20.9	19.9	20.0	19.6	19.4	19.0	18.2	19.7	1630	1970-95
Punta de Agua	24.6	25.8	27.6	29.7	31.0	30.4	28.1	28.1	28.0	28.3	26.5	25.3	27.8	279	1975-85
Taretan	19.8	20.7	22.2	23.9	24.8	24.1	22.7	22.6	22.4	22.4	21.4	20.7	22.3	1170	1958-96
Uruapan	16.7	17.3	19.4	21.2	21.7	21.2	20.3	20.2	20.1	19.7	18.5	17.5	19.5	1610	1963-96
Tancítaro	3.0	0.0	2.0	4.0	10.7	15.0	16.2	16.2	14.5	10.5	4.0	3.0	8.3	3800	2002

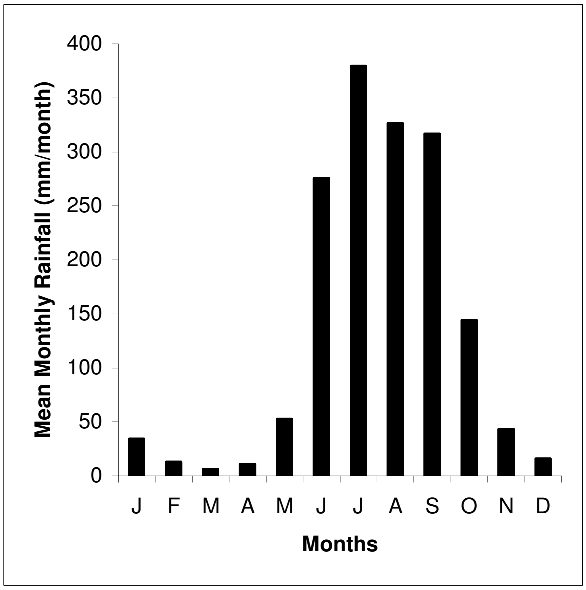


Figure 3-5 Mean monthly precipitation

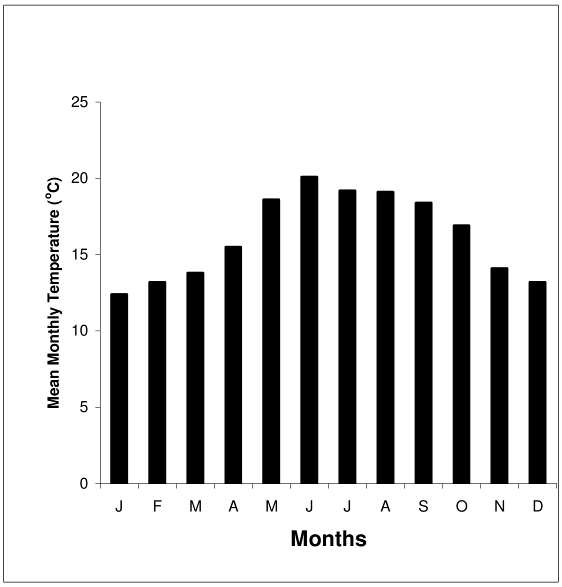


Figure 3-6 Mean monthly temperature

3.3.4. Geology and Geomorphology

The geology and geomorphology of the study area is highly influenced by volcanic activities. According to Pulido and Bocco (2003) the geology of the study area is characterized by recent basaltic and andesitic materials. In terms of geomorphology, the major landscape units in the study area include the mountains and piedmonts. These landscape units are further divided into volcanic domes, cones, lava flow terraces as well as accumulational terraces as the dominant relief types. The major landforms found in the study area include the slope facet complexes and treads and risers of terraces.

3.3.5. Soils

Soils of the Zacándaro sub-watershed include the Regosols, Inceptisols, Leptosols, Luvisols, Cambisols and Andosols. These soil types vary within and between the landscape units. The details of soils types found within the study area will be discussed under the results and discussions.

3.3.6. Vegetation and land use

A considerable portion of the study area is still under natural vegetation, however in some parts deforestation in search for agricultural land and other forest product is replacing the original natural forest. According to Pulido and Bocco (2003), the dominant land cover is characterised by humid and sub humid temperate forest consisting of tree species such as *Pinus leyophyla, Pinus michoacana, Pinus montezumae, Quercus sp., Abies religiosa and Alnus sp.*

Major land use types are subsistence agriculture (maize), extensive grazing, orchard (mainly Avocado and Peaches) and forestry especially in the upper part of the study area. Figure 3-7 shows the land use/land cover of the Zacándaro sub-watershed

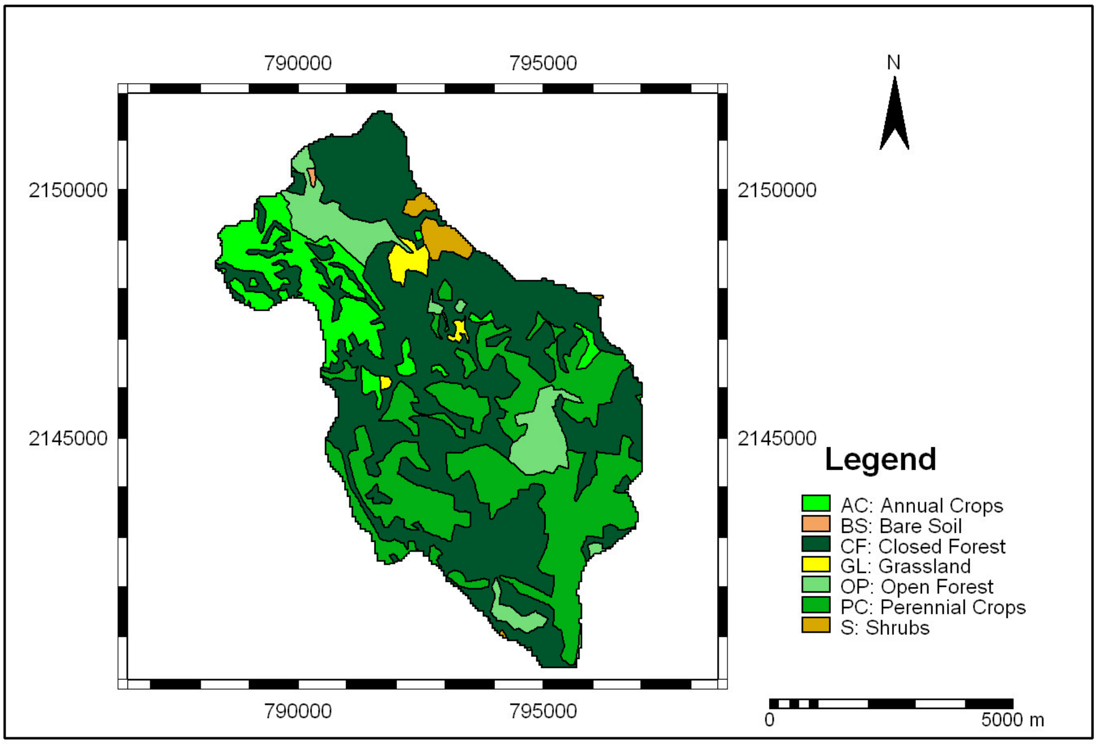


Figure 3-7 Land use/Land cover map of the Zacándaro sub-water shed

3.4. Data collection

3.4.1. Pre-field work

Aerial photo interpretation of panchromatic aerial photographs of April 1995 at a scale of 1:75000 and preliminary legend construction based on the geo-pedological approach (Zinck, 1988) were carried out. After the initial geo-pedological interpretation, boundaries delineated during the interpretation were visually transferred to the printed hard copy of the hill-shaded image generated from DEM. Sample areas for detailed geo-pedological studies in the field were then selected. Steps used in generating the hill-shaded image using DEM are briefly described below.

The DEM (described in subsequent chapters) was filtered to produce shaded relief map to assist in both the geo-pedological aerial photo interpretation and transferring of delineated boundaries of geo-pedological mapping units into the printed hard copy. The shaded relief model was also used to generate stereo pair from DEM operation, where the boundaries were then transferred to this stereoscopic model using on-screen digitisation and screen scope used to visualize three dimensions.

3.4.2. Fieldwork stage

This phase involved the collection of primary and secondary data from the field. Prior to actual data collection in the field a reconnaissance survey was made to understand the soil landscape relationship. Techniques used in collection of topographic, climatic, soils and vegetation data used in this study are described below.

(a) Climatic data

In order to run the soil erosion and soil water balance models, detailed climatic data are needed. Data needed to run these models include rainfall amount, number of rain days, mean monthly temperature, potential evapotranspiration as well as actual evapotranspiration. All the climatic data used were obtained from the Department of Ecology of The National University of Mexico. Climatic data collected included the daily rainfall, mean monthly rainfall as well as mean monthly temperature from thirteen meteorological stations for the period of 25 and 56 years. Unfortunately other data needed to run the models were not available from the existing data of the meteorological stations since they record the only basic climatic data.

(b) Soil data

Soil data were collected directly from the field. Soil inventory was based on geo-pedological approach using aerial photo interpretation (Zinck, 1988). Soil observations were made on minipits and from auger holes. Profile description was made according to FAO guidelines for profile description (FAO, 1990). Soil andic properties were determined directly from the field based on the procedure described in Manual for Field Soil Description (Siebe et al., 1996). The procedure involves the use of 1% phenolphthalein indicator and Sodium Fluoride (NaF) to determine the active aluminium, which is an indicator of presence of andic properties in the soil. Since the existing soil maps prepared by INEGI (1983) and Siebe et al. (2003) use the FAO soil classification system (FAO, 2001), the same classification system was adopted in this study.

Soil data such as particle size distribution are important in running of models as they are used to estimate other parameters based on pedo-transfer functions. Organic matter content is used in the assessment of aggregate stability determined in the simple field tests. Soil samples were collected from representative sites for laboratory analysis of particle size distribution, organic matter content and bulk density from representative sites as follows:-

Bulky density

Core rings of known volume were driven into soils using a wooden stick put on the top of the ring. The rings were carefully removed and a knife used to level the soils in the cases where the ring came out with soils beyond its limit. In each site three representative samples were taken.

Surface cohesion

A shear vane apparatus was used to measure the surface cohesion. Procedures used to measure surface cohesion are described in section 3.3.3 under the simple field tests.

Simple field tests

In order to assess soil erodibility and erosion hazards in the field, simple field tests were carried out at each sample location following procedures described by Kunwar et al. (1999).

Semi quantitative assessment of soil erosion features

Recording of soil erosion features for semi-quantitative assessment was carried out following the procedures described in section 3.2.3. The results of semi quantitative assessment of soil erosion features are given in Appendix 1.

(c) Vegetation and land use data

Data collected on, surface cover (%), plant canopy (%) and plant height were collected as follows:-

Ground cover (GC)

Surface cover was estimated using the FAO surface cover estimation chart, which consists of 10 squares boxes with divisions in four quarters in each square box and corresponding percentage for each box square. The field surface was visually compared with squares box chart. The value of the box square with a distribution that closely corresponds with the observed field surface was taken for the site.

Canopy cover (CC)

Canopy cover was estimated using a methodology described by Yazidhi (2003). A tape was laid down on the ground based on the visual site of the upper canopy of 10 trees. A radius value was derived and canopy area computed as πr^2 . The distance between individual trees was determined and the area computed. Percentage canopy cover was finally computed as canopy area divided by plot area and multiplied by 100. For short vegetation such as maize shrubs, the sighting technique was used to estimate canopy cover. A mirror was put on the surface and the percentage canopy estimated based on how much is reflected on the mirror surface area.

Plant height (PH)

For erosion modelling data on plant height for estimating leaf drainage is required. For short vegetation such as maize and shrubs, plant height was measured directly using a measuring tape. For tall trees, plant height was estimated using a clinometer by measuring angles at the top and base of the tree. The overall height of the tree was obtained by summing up two heights as shown below:

$$H1 = \tan(A1) * d \qquad \text{Equation 3-30}$$

$$H2 = \tan(A2) * d \qquad \text{Equation 3-31}$$

Where A1 and A2 are top and bottom angles.
H1 and H2 are heights of the top and bottom angles
d : estimation distance.

The methodological steps followed in data collection are shown in Figure 3-8

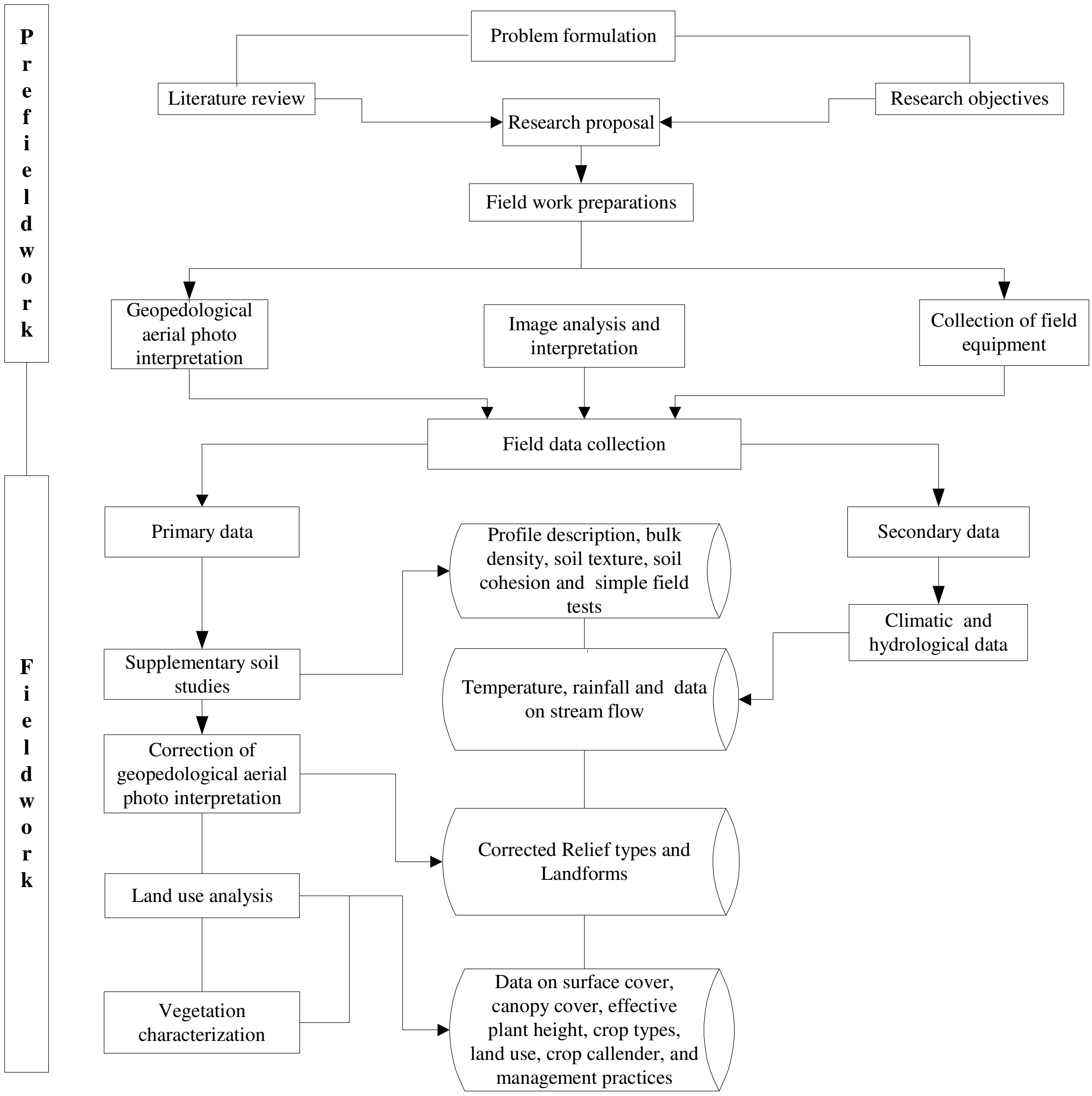


Figure 3-8 Methodological flow chart for data collection

4. Data Processing and Analysis

4.1. Data input

All the data collected from the field were entered into the ILWIS® database system, the data were transformed in a format acceptable to run the models in a GIS environment. From the data various thematic layers related to vegetation and soil parameters were generated. Required parameters for map calculations were entered and encoded according to each model i.e. the erosion and soil water balance models

4.2. DEM generation

Topographic information required to run the RMMF model include the slope gradient. One of the techniques used to generate the slope map is the use of DEM. DEM in this study was also used to generate other parameters that shows a correlation with elevation such as precipitation, temperature and number of rain days in a year. DEM generation was based on the existing digital contour map at 20 m interval provided by the Geography Department of The National University of Mexico. Contour interpolation using the existing algorithm in ILWIS® was performed resulting a DEM with 20 m pixel size. Twenty meters pixel size was selected for interpolation since the contour intervals were 20 m.

4.3. Processing of satellite data

Three satellite images were pre-processed and prepared for visual interpretation. The available satellite data were LandSat ETM+7 of October 2000, the ASTER level 1A of October 2001 and March 2003. The LandSat ETM+7 images were geometrically and radiometrically corrected by the Institute of Geography of The National university of Mexico. They have a RMS error of 0.95 (28.5 m). The radiometric correction was based on dark object subtraction principle. LandSat ETM+7 images were then stretched applying a *linear contrast stretch* followed by development of false colour composites using different band combinations to visualize the geo-morphological features and land use/land cover of the study area.

The Aster images were imported into the GIS software ILWIS®. The raw Digital Numbers of the ASTER file were then converted to the sensor digital number values[1]. Resampling was applied to the bands to make it possible for their combination and visualization. The resampling algorithm was the *Nearest Neighbour.*

Due to the presence of noise in the SWIR bands of ASTER a standard average filter (average filter 3X3, with a gain factor of 1/9=0.111111, ILWIS® User Guide, 2002) was applied. This was then fol-

[1] Sensor calibrated DN values are corrected radiance values scaled back into an appropriate range, this case from 0 to 255

lowed by an application of edge enhancement filter (filter of 3X3, with a gain factor of 1/8=0.125; ILWIS User Guide, 2002), this enhanced the relief and land cover features.

4.4. Updating the land use/ land cover map

In order to have more recent land use land cover map of the study area, the existing map (Fuentes, 2000), was updated using recent satellite images of October 2001 and April, 2003, however the improvement were only limited. The updating procedures involved the use of ground truth (GPS survey) collected during the fieldwork followed by visual interpretation through screen digitisation. A stereo pair from DEM and FCC was generated to have a three-dimensional view of the terrain. The results were viewed using the screen stereoscope device and ILWIS® GIS software. The existing land use segment map was added onto the three-dimension model and land use/land cover classes were adjusted whenever it was necessary using field data. The resulting land use/land cover map was later used to generate various vegetation attribute maps used in running the models.

4.5. Laboratory analysis of soil samples

Representative soil samples collected from the field were brought to laboratory for bulk density, organic matter and particle size distribution analysis.

(a) Bulk density

Core rings with soil samples were oven dried at 115^0C for 24 hours. After 24 hours the weights of core rings plus oven-dried sample were taken followed by determination of empty core rings. The difference of the weight of core rings plus oven-dried soil minus the weight of the empty core ring gave the weight of dry soil. For each core ring its diameter and height was measured and the volume calculated. The bulk of each sample was obtained by dividing the weight of oven-dried sample and the volume of the core ring. The results of the bulk density determination are given in Appendix 1.

(b) Organic matter content

The organic matter content was determined using a "Loss-on-Ignition" method (Nelson and Sommers, 1996). Known weight of soil samples were dry-ashed and weight loss determined after-ashing was taken as organic matter content of the sample. For quality control, a sample with known carbon content was also included. The results of analyses of organic matter content are given in Appendix 1.

(c) Particle size distribution

Particle size distribution was determined using the Pipette method as described in ISRIC's procedures for soil analysis (ISRIC, 1995). Twenty grams of fine earth was weighed in a beaker. In order to remove the organic matter, 15 ml water and 15 ml H_2O_2were added and left over night to allow reaction to take place. The next day the beakers were placed on water bath at 80 ^oC until the decomposition of organic matter was complete. To the samples 300 ml of water was added, placed on a hot plate and boiled for 1 hour to remove any remaining H_2O_2 and allowed to cool. The materials were allowed to settle and the excess water was siphoned out. The suspension was quantitatively transferred to 1 litre polythene bottle and 20 ml dispersing agent was added (Sodium hexametaphosphate 4% and soda 1% solution). The samples were then shaken for 16 hours in an end-to-end shaker at a speed of about 30 rpm. The samples were then transferred to sedimentation cylinders by passing the suspension through a 50µm sieve. Materials trapped on a 50µm sieve were then sieved to determine sand fractions. Silt and clay fractions were determined by pipetting 20 ml of suspension at a predetermined time and depth and drying at 105 ^0C over night. Using appropriate formula the silt and clay fractions were determined. For quality control, two samples with known clay percentages were included in particle size analysis. Results of the particle size analyses are given in Appendix 1.

4.6. Generation of input parameters for the Thornthwaite and Mather (1955) model

Factors required to run Thornthwaite and Mather (1955) model were generated as attributes. Details of the Techniques used to generate the available water holding capacity of soils, monthly rainfall, monthly potential and actual evapotranspiration and run off coefficient are explained in the following sections.

4.6.1. Generation of available water holding capacity of soils

Available water holding capacity of soils is a function of the texture and rooting depth of the vegetation. The available water holding capacity of soils of the study area was generated from the geo-pedological map and land use/ land cover map prepared during this study. From geo-pedological map soil texture attribute map was created, this was crossed with the land use/land cover map to have an indication of the relationship between land cover and soil texture. The available water capacities were assigned to the combined classes of soil texture and land use/ land cover types cross table using information from Tables 2-1 and 2-2. Where the soil horizons had different textural classes, a weighted average was used to assign water holding capacities based on the horizon thickness. The individual water holding capacities in each horizon were then added up to get the maximum water holding capacity of the profile at rooting depth. Available water capacity of soils was then generated as an attribute map. Attribute table for assigned available water holding capacity is given in Appendix 2.

4.6.2. Generation of monthly rainfall maps

Using the Pearson's Product Moment Correlation, analysis of the relationship between monthly rainfall and altitude was carried out. Equations were derived to generate monthly rainfall map based on DEM. Equations used in generation of monthly rainfall maps are given in Appendix 3.

4.6.3. Generation of evapotranspiration map

No measured data on evapotranspiration exist in the study area, and therefore the monthly evapotranspiration was estimated using temperature method (Thornthwaite and Mather, 1957). Pearson's Product Moment Correlation was used to analyse the relationship between altitude and mean monthly temperature data from thirteen meteorological stations located close to the study area. The results showed that there was a very strong correlation between these parameters. Equations used to generate monthly temperature maps are given in Appendix 3.

The monthly mean temperature output maps were used to calculate the monthly standard evapotranspiration using the Thornthwaite and Mather (1957) method, which is described in section 3.2.1 under the soil moisture modelling. The monthly standard potential evapotranspiration were then adjusted with correction factor based on the number of days in a month and length of the day. These factors are depending on latitude and are shown in Table 4-1.

Table 4-1 Correction factors for adjustment of standard potential evapotranspiration

LATITUDE	JAN.	FEB.	MAR.	APR.	MAY.	JUN.	JUL.	AUG.	SEP.	OCT	NOV.	DEC.
20^0N	0.92	0.96	1.00	1.05	1.09	1.11	1.10	1.07	1.02	0.98	0.93	0.91

The actual evapotranspiration in this study was estimated as crop evapotranspiration. The crop evapotranspiration is obtained by adjusting the potential evapotranspiration using a crop coefficient (Kc). According to Allen et al. (1998), the effect of crop transpiration and soil evapotranspiration is combined into a single Kc coefficient. The coefficient integrates differences in the soil evaporation and crop transpiration rate between the crop and the grass reference surface. The crop coefficients are obtained by considering different stages of crop development namely initial-stage, crop development stage, mid-season stage and late-season stage. Monthly crop coefficient maps were generated as attribute maps of the land use/land cover and then overlaid with the adjusted potential evapotranspiration maps to estimate actual evapotranspiration as a function of crop evapotranspiration. The individual monthly potential and crop evaporation were then summed up to the respective annual potential and crop evapotranspiration using map calculations. Table 4-2 shows the monthly crop coefficients used in this study.

Table 4-2 Crop coefficients used to estimate crop evapotranspiration

Land cover type	Jan	Feb	Mar	Apr	May	Jun.	Jul.	Aug.	Sep	Oct	Nov	Dec
Annual Crops	0.35	0.35	0.35	0.35	0.65	1.2	1.2	0.35	0.35	0.35	0.35	0.35
Bare Soil	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Closed Forest	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90
Grass Land	0.30	0.30	0.30	0.30	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.30
Open Forest	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85
Perennial crops	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85
Shrubs	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80

(Source: Allen et al., 1998; Morgan, 1995, Thornthwaite and Mather, 1955)

4.6.4. Generation of runoff coefficient

In the Thornthwaite and Mather (1955) model, the run off coefficient is assumed to be a constant value for the whole catchment. This appears to be unrealistic as there is spatial variation on the runoff coefficient as affected by land cover and soil factors. In normal hydrological studies, the runoff coefficient from the gauged catchment is determined from the recorded hydrographs. The Zacándaro sub-watershed is un-gauged and therefore the hydrographs are not available. The spatially distributed run-off coefficient used in this study was estimated by dividing the results of the estimation of annual run-off in the RMMF model by annual rainfall. The coefficient obtained was assumed to be same on monthly basis.

4.7. Modelling soil moisture

Computing the water balance on monthly basis involves an assumption that rain falls at a constant low intensity throughout the month. One of the difficulties in computation of water balance is the initial soil moisture content of the soil. In this it was assumed that at the end of rain season (October) the soil moisture content is equal to the soil's available water holding capacity and water balance calculations stated in November during the dry season. For the purpose of this study, the ground water recharge (GRECH) is referred to as excess moisture.

After all the input parameters needed for running the Thornthwaite and Mather model have been prepared in a raster based format, the model was applied using map calculation procedures in ILWIS® program.

4.7.1. Estimation of monthly effective rainfall and surface runoff

To obtain the monthly surface runoff, the monthly amount of rainfall reaching the surface (section 4.6.2) was overlaid with the runoff coefficient layer generated in section (4.6.4) as per equation (3-4). The monthly effective rainfall was then obtained by deducting the monthly surface runoff from the monthly rainfall reaching the surface.

4.7.2. Estimation of monthly surface recharge

From the total amount effective rainfall that reaches the surface, part of it is returned to the atmosphere through evapotranspiration. The monthly surface water recharge was estimated from the monthly effective rainfall (section 4.7.1) and crop evapotranspiration generated in section 4.6.3 as per equation 3-7.

4.7.3. Estimation of monthly soil moisture

Soil moisture depends on amount of surface recharge and available water holding capacity of soil. When soil was not at its water holding capacity and surface recharge (SRECH) is positive, soil moisture in the present month was estimated as a sum of soil moisture in the previous month plus amount of surface recharge in the present month (equation 3-8). In months where the surface recharge was negative (effective rainfall is less than evapotranspiration) i.e. water is withdrawn from the soil, the soil moisture was estimated as a function of accumulation potential loss using equation 3-10. The accumulated potential water loss was estimated using the equation 3-11. When the previous month (I-1 i.e. October) was followed by the present month (i.e. November) with water deficit, the starting accumulated potential water loss was estimated using the equation 3-12.

4.7.4. Estimation of monthly excess soil moisture

For the purpose of this study, excess soil moisture was estimated as any moisture that is in excess of available water holding capacity of soil. Equation 3-9 was used to estimate the excess soil moisture.

4.8. Generation of input parameters for the RMMF model

In order to run the revised MMF model some of the parameters that were not available from field studies were estimated and generated using other observable parameters. These input parameters include the annual rainfall amount, slope steepness, soil moisture at 1/3 bar and number of rain days. Details of the techniques used to generate these parameters are explained in the following sections.

4.8.1. Generation of annual rainfall map

The generation of the annual rainfall layer was based on long term rainfall data from the twelve meteorological stations located close to the study area. Pearson’s Product Moment Correlation was used to analyse the relationship between annual rainfall in different stations and altitude. The results showed a significant positive correlation between the annual rainfall and the altitude with r^2 value of 0.6333. Study area was masked and annual rainfall map was generated using map calculation procedures in

ILWIS®. Figure 4-1 shows the relationship between annual rainfall and elevation, and the equation used.

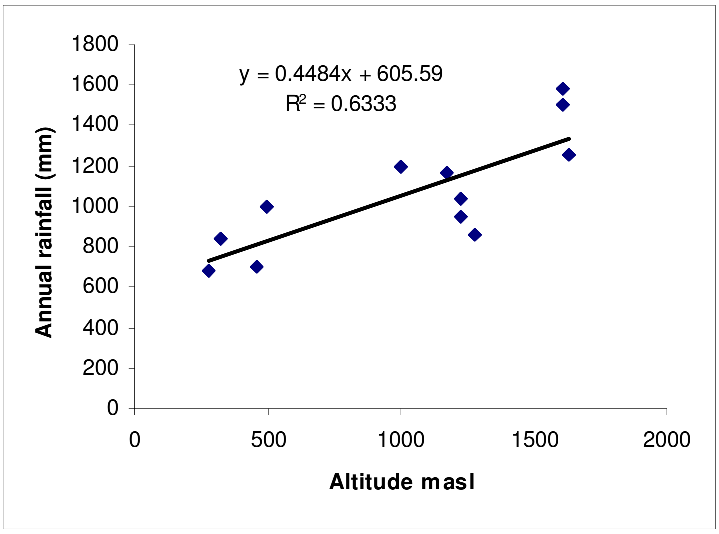


Figure 4-1 Relationship between annual rainfall and altitude

4.8.2. Generation of slope steepness map

The slope steepness map was generated from DEM using linear filtering operations. The filters work in 1 by 5 environment, it calculates the first derivative in x direction (df/dx) per pixel (gain factor, 1/12 = 0.0833333) and in y direction (df/dy) per pixel (gain factor, 1/12 = 0.0833333; ILWIS User Guide, 2002). The slope steepness is then calculated as percentage using the following syntax:

Slopemapinpercentage = 100* HYP (Dx,Dy)/Pixel Size (DEM)

The output from the above process is then transformed to degrees using the syntax:

Slopemapindeg. =RADDEG(ATAN(Slope map in percentage/100))

4.8.3. Generation of canopy cover map

The canopy cover map used in this study was generated using an attribute of the land use/cover map. The canopy cover values estimated from the field needed to generate the attribute map were entered in attribute table linked to the land use/cover map. The percentage vegetation cover of maize varies with the stage of growth and therefore the values obtained in the field were then adjusted to reflect an average canopy cover over the growing period. The canopy cover for maize was adjusted using the guide value of 42 percent provided in Morgan (1995). Other types of land cover such as bare soil, closed forest, open forest, grassland and shrubs were assumed to remain unchanged throughout the year, and therefore the values estimated in field were used without any adjustment.

4.8.4. Estimation of moisture content at field capacity

Andosols and allophane containing soils have been reported to have higher moisture content at field capacity than other mineral soils. In this study, moisture contents based on guide values provided by Morgan (2001) were adjusted by a factor of 1.3 based on the textural class. The basis for such an adjustment factor comes from the study of Armas-Espinel et al. (2003). They have reported that water-holding capacity at low suctions was closely related to andic diagnostic properties. Analysis of their results based on 49 undisturbed core samples collected from a depth between 0-30 cm has shown that average moisture storage capacity at 1/3 bar was higher by between 20 to 40 percent than those expected based on soil texture classes. Results of the study by Siebe et al. (2003) closely relate to the study conducted by Armas-Espinel et al. (2003). Based on these analyses, a mean value of 30 percent was taken to adjust the moisture content of soils of the study area as estimated by soil texture based on guide values given by Morgan (2001). Soil moisture at field capacity was then generated as an attribute of the geo-pedological map.

4.8.5. Generation of number of rain days

For erosion modelling using the RMMF, data on number of rain days is required. The generation of rain-days-map was based on the analysis of long-term rainfall data from twelve meteorological stations. Pearson's Product Moment Correlation was used to analyse the relationship between altitude and number of rainy days. Results revealed that there was a strong correlation between total number of rainy days in a year and altitude with r^2 value of 0.9344 (Figure 4-2)

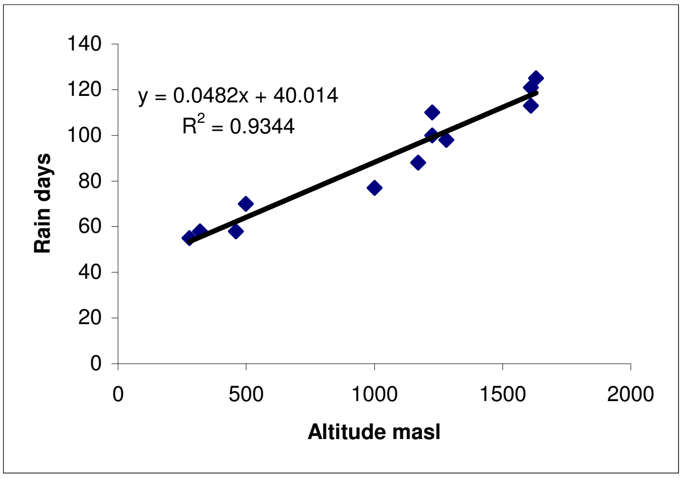


Figure 4-2 Relationship between number of rain days and altitude

Table 4-3 summarizes GIS input parameters needed to run the RMMF model and methods used to generate or estimate the respective parameters.

Table 4-3 GIS in put parameters for the RMMF model

In put parameters	Data source/methods
Rainfall	Monthly records from 12 stations close to study are
MS (moisture content at field capacity	Adjusted guide values based on literature c
BD (Bulk density (Mg/m^3)	Determined from collected samples
EHD (Effective Hydrological depth of the soil)	Literature according to crop type and conditions observed in the field
Et/Eo (Ratio of actual to potential evapotranspiration)	Estimated by Thornthwaite and Mather (1957) and Crop coefficients (Kc)
K (soil erodibility index	Literature according textural class
S^0 (Slope gradient	From the Digital Elevation Model (DEM)
C crop cover management	From literature according to crop type
CC (Canopy cover)	Measured in the field
PH (Plant Height)	Measured in the field
GC (Percentage ground cover)	Determined in the field using FAO guidelines

4.9. Modelling soil erosion

After all the input parameters needed for running the RMMF have been prepared in a raster format, the model was applied in ILWIS® using map calculation procedures. Broadly, the input parameters can be grouped as rainfall, soil, landform and land cover parameters. Soil and land use parameters are summarized in Tables 4-4 and 4-5 respectively. Stepwise procedures used in running the model are given in the subsequent sections.

Table 4-4 Soil parameters used in soil erosion modelling

Mapping Unit	COH	BD	Z	MS	K
Pi111	3.4	0.92	0.6	0.36	0.7
Pi211	1.9	0.63	1.1	0.36	0.7
Pi221	3.4	0.92	0.6	0.36	0.7
Pi311	2.8	0.63	0.7	0.18	0.3
Pi411	3.3	0.94	0.6	0.18	0.3
Pi421	1.2	0.94	1.7	0.36	0.7
Pi431	1.8	0.78	1.1	0.36	0.7
Pi511	1.4	1.14	1.4	0.1	1.2
PM111	2.7	0.96	0.7	0.18	0.3
PM211	2.7	0.96	0.7	0.18	0.3
ZP111	1.9	0.63	1.1	0.36	0.7
ZP211	3.4	0.76	0.6	0.36	0.7
ZP311	1.8	0.78	1.1	0.36	0.7
ZP321	1.8	0.78	1.1	0.36	0.7
ZP411	2.5	0.74	0.8	0.36	0.7
ZP421	2.9	0.73	0.7	0.36	0.7

Table 4-5 Land use parameters used in soil erosion modelling

Land use	A	CC	C	GC	PH	EHD
Annual Crops	0.25	0.42	0.2000	0.15	1.90	0.12
Bare Soil	1.00	0.00	1.0000	0.00	0.00	0.09
Closed Forest	0.30	0.85	0.0015	0.65	23.10	0.20
Grass land	0.33	0.90	0.0055	0.80	0.30	0.14
Open Forest	0.25	0.53	0.0010	0.50	17.65	0.15
Perennial Crops	0.25	0.61	0.2000	0.60	7.30	0.12
Shrubs	0.25	0.40	0.0010	0.20	2.70	0.12

4.9.1. Estimation of rainfall energy

The inputs used to estimate rainfall energy were annual rainfall amount, plant rainfall interception factor, canopy cover and plant height. The annual rainfall map generated in section 4.8.1 was used. Plant rainfall interception rates ranging from 0-1 for the respective covers in the study area were taken from Morgan (1995). The plant rainfall interception rates were entered in an attribute table linked to the land use map. The canopy cover map, generated in section 4.8.3, was used as an input in estimating rainfall energy. The annual rainfall layer was overlaid with the crop rainfall interception layer following equation (3-16) which resulted in effective rainfall map. The revised MMF distinguishes the kinetic energy of rain into two components i.e. kinetic energy of direct throughfall and kinetic energy of leaf drainage. The effective rainfall map was split into two maps i.e. leaf drainage map obtained as a function canopy cover (equation 3-17), and the direct throughfall map computed as effective rainfall minus leaf drainage (equation 3-18). A kinetic energy of rainfall map was then calculated using map calculation function with relational equation (Wischmeier and Smith, 1978) that is more reflective of the rainfall energy-intensity relationship of the study area. The rainfall intensity value of 25 as suggested by Morgan (2001) for tropical countries was used. A kinetic energy map of leaf drainage was also generated as a function of plant height. The two maps were added together to obtain the rainfall energy map of the study area.

4.9.2. Estimation of runoff

Runoff was estimated from annual rainfall, moisture storage capacity of soil and annual number of rain days. The annual rainfall generated in section 4.8.1 was used. The annual rainfall map was divided by average rain days generated in section 4.8.5 to obtain the mean rain per day. Soil moisture storage capacity was estimated as a function of bulk density, soil moisture content at field capacity, effective hydrological depth and the ratio of actual to potential evapotranspiration. Values for parameters used to calculate soil moisture were obtained from laboratory analysis of soil samples, values suggested by Morgan (1995, 2001), as well as other data generation techniques as summarized in Table 4-3. Parameters required to run the model were generated as attributes from the geo-pedological and land use maps. These maps were then overlaid using appropriate equation (3-21) to obtain the soil moisture storage capacity. The annual runoff layer was finally generated as a combination of annual rainfall map, soil moisture storage capacity and mean rain day as per equation (3-23).

4.9.3. Estimation of soil particle detachment

Soil particle detachment was obtained in two phases. In the first phase, a soil detachment map by raindrop impact was computed by overlying the total kinetic energy layer with soil erodibility map following equation (3-24). The guide erodibility values (Morgan, 2001) needed to generate attribute map were entered in the table linked to the geo-pedological map and an attribute map was generated. In the second phase, a soil detachment map by runoff was computed using slope steepness obtained from DEM, annual runoff, resistance of soil and ground cover (equation 3-26). The surface cover and soil resistance maps were generated using data collected from the field. Values of ground cover and soil resistance derived from the surface cohesion were entered in the attribute tables linked to the geo-pedological and land use maps. Layers for surface cover and soil resistance were then generated as attributes from the geo-pedological and land use maps. Total soil detachment was finally obtained by adding the soil particle detachment r by runoff to the soil particle detachment by raindrop impact.

4.9.4. Estimation of transport capacity of runoff

The transport capacity of overland flow (runoff) depends on the amount runoff, slope gradient and crop management factor. The crop management factor was generated using the typical values from plant parameters given in Morgan (1995). Values of Crop cover management factor were entered in attribute table linked to the land use map. Crop cover management factor layer was then generated as an attribute of the land use map. The transport capacity of runoff was then generated from runoff (section 4.9.2), slope steepness (section 4.8.2) and the crop management factor as per equation (3-28).

4.9.5. Estimation of soil loss rate

To obtain annual soil loss predictions, the estimated transport capacity (TC) and total detachment (D) maps were compared in each grid. The minimum of the two was taken as the estimated annual soil loss denoting whether the soil detachment or transport capacity by runoff is the limiting factor. The results of the model (Kg/m^2) were converted to tons/ha/yr.

4.10. Analysis of simple field test data

Simple field tests were carried in order to assess soil erodibility and erosion hazards in different mapping units. These included crumb, manipulation, rainfall acceptance, pinhole and shear vane tests. Results of the simple field tests were analysed to get general information on the main aspect of soil erodibility and soil erosion hazards. The evaluation of the results of the simple field tests was done based on ranking. The ranking was according to the rating classes recorded in the field. The test results were ranked for the following parameters.

- Availability of erodible material
- Overland flow production,
- Resistance to scour, and
- Inter-rill and rill erodibility.

Using the dry crumb and manipulation tests, the availability of erodible materials is assessed. Overland flow production was assessed by rainfall acceptance test, while the resistance to scour was assessed by pinhole and shear vane tests.

4.10.1. Availability of erodible materials

The results of dry crumb and manipulation tests are used for assessing the availability of erodible material. In evaluating these tests weight is given to each tests result, as their rating classes are different. The dry crumb test has 1-4 classes, however, manipulation test has 1-7 classes. In order to keep the gap of their rating proportional, the dry crumb test result was multiplied by two (2) and the manipulation by one (1) to assess for material availability. In this way the sum of the weighted rates are ranked for availability of erodible material. Five (5) general material availability classes were obtained (Table 4-6).

Table 4-6 Ranking table for availability of erodible material

Material availability classes	Sum of crumb and manipulation test values
Very low (1)	1-3
Low (2)	4-6
Moderate (3)	7-9
High (4)	10-12
Very high (5)	13-15

4.10.2. Overland flow production

Overland flow production was evaluated from the results of rainfall acceptance test. Ranking was done for the various sample sites by considering the amount water is infiltrated in one-hour time, which is estimated from infiltration curves. In evaluating the rainfall acceptance for overland flow production, the test results was arranged on the basis of a system of five general classes as given in Table 4-7. The results range from 5.4-63.1 cm/hr. Therefore, sample sites with high amounts of infiltration rates were ranked low and those with low amount were ranked as high (Table 4-7).

Table 4-7 Ranking table for overland flow production

Infiltration rate (cm/hr)	Overland flow production test classes
5.4 – 16.9	Very high (5)
17.0 - 28.4	High (4)
28.5 – 39.9	Moderate (3)
40.0 – 51.4	Low (2)
51.5 – 63.0	Very low

4.10.3. Resistance to scour

Resistance to scour of the topsoil is estimated by pinhole and shear vane tests. These test give an idea of the shear resistance of the topsoil to scour by concentrated flow. The rating class for pinhole is 1-4 classes, however, the shear vane test is measured in kPa and results from range from 1.2-3.5. Thus, each of the tests was ranked separately into four classes based on the field test results as indicated in Tables 4-8 and 4-9.

Table 4-8 Ranking table for pinhole test

Pin hole test classes	Pinhole rating ranges
Very low (1)	1
Low (2)	2
Moderate (3)	3
High (4)	4

Table 4-9 Ranking table for shear vane test

Shear vane test classes	Shear vane measured values ranges in classes
High (4)	1.2 - 1.7
Moderate (3)	1.8– 2.2
Low (2)	2.3–2.7
Very low (1)	2.8– 3.5

The ranks for pinhole and shear vane are summed up to get resistance to scouring. Subsequently, the tests are ranked again on the basis of the summed rankings. As it was done in the ranking of the material availability and overland flow, the sum of the rankings was arranged on the basis of a system of four general classes as shown in Table 4-10.

Table 4-10 Ranking table for resistance to scour

Resistance to scour classes	Sum of ranks of the pinhole and shear vane
Very low (1)	1.0 – 2.0
Low (2)	3.0 – 4.0
Moderate (3)	5.0 - 6.0
High (4)	7.0 – 8.0

4.10.4. Inter rill and rill erodibility

Inter-rills are the uniform thin layer removal of the soil surface. Rillibility is the sensitivity of the soil for rill formation. In determining and evaluating the inter rill erodibility, availability of erodible material and overland flow production are considered. Thus, the lower of the resulting ranks of material availability and overland flow production are taken as an indication of the most limiting factor for the inter rill erodibility of the soil. The soils were again ranked according to the limiting factor to know the inter rill erodibility classes for each of the sample area.

The rill erodibility was estimated based on the rankings of overland flow production and resistance to scouring. Therefore, the lowest of the resulting ranks of overland production and resistance to scour was considered as an indictor of the most limiting factor for rill erodibility. Ranking was done again based on the limiting factor for the rill erodibility. In this way the rill erodibility was determined for each of the sample points.

Finally, the ranks of the inter rill and rill erodibility are summed up to rank them for estimation of the qualitative soil erodibility classes. The final rank was classified on the basis of a system of four (4) general soil erodibility classes.

4.11. Analysis of semi-quantitative assessment of soil erosion features

To assist in the evaluation of the performance of the RMMF model, a semi quantitative assessment of soil erosion features was carried out as described in section 3.2.4. Evaluation of data from the semi quantitative assessment of erosion feature involved the computation frequencies (ranging between 0-4) of erosion features in order to obtain of soil erosion indices. Soil erosion index for each functional segment was calculated using equation 3-29.The erosion indices from three functional segments at each representative site were added and averaged to obtain mean soil erosion index for each representative site. A point map using the coordinates of each sample points was generated and using the pixel information window, the soil loss rates at each point were picked. A Pearson’s Moment Correlation Coefficient was calculated between soil erosion indices and soil erosion rates.

4.12. Evaluation of model results

Data analysis involved simple statistical operation to test the validity of formulated hypotheses and model results. The statistical operations included Pearson’s Product Moment Correlation and map correlation between annual soil loss and annual soil water content. Descriptive statistics such as mean, standard deviations as well coefficient of variation was used.

The evaluation of performance of the RMMF model was based on simple field tests, semi quantitative assessment, sensitivity analysis, and comparison of soil loss rates from plot data and other model results. For soil water balance model, the evaluation was based on comparison of annual surface runoff and annual stream flow data.

In simple field tests, parameters contributing to the erodibility were related to the erosion rates predicted by the model. The qualitative soil erosion hazards classes were also compared to the predicted soil erosion rates.

Soil erosion indices calculated in the semi quantitative erosion assessment was compared with the soil erosion rates predicted from soil erosion modelling. A point map of the soil erosion indices was prepared and overlaid on the soil erosion rates calculated by RMMF model. Using the pixel information window, soil erosion rates were extracted and correlated with the semi quantitative assessment of soil erosion

In sensitivity analysis, local sensitivity analysis (Campolongo et al., 2000) was used. In this method, parameters of the model i.e. slope gradient, rainfall amount and moisture storage capacity of the surface soil were changed by percentage values while holding others constant. The model was then run using the changed values in a particular parameter and soil loss rates generated. Percentage changes in soil loss resulting from changed parameter values were then calculated and evaluated accordingly.

Soil erosion rates predicted using the RMMF model were also compared with the soil rates from experimental plots and other physically based models in the Patzcuaro watershed.

5. Results and Discussion

This chapter presents the results soil studies, soil moisture modelling, soil erosion modelling, simple field tests and semi-quantitative assessment of soil erosion features and with respect to the Zacándaro sub-watershed. The influence of land use and landscape position and their relative contribution to the predicted soil erosion rates also is evaluated. Predicted soil erosion rates are further compared with erosion hazard classes generated using simple field tests as well as results of the semi quantitative assessment. The results of available soil moisture modelling are evaluated in terms of the spatial distribution and the interaction between vegetation and soil hydrological properties. The relationship between modelled annual soil erosion rates and available soil moisture at the rooting depth is further evaluated to see their relationship. Finally, the performance of the models as conservation planning tools is evaluated.

5.1. Soil landscape relationship

The geo-pedological map of the study area is a result of soil studied in the representative mapping units and previous works done in the study area (INEGI, 1983; Siebe et al., 2003). Based on the geo-pedological approach (Zinck, 1988), the soils of the Zacándaro sub-watershed can be described under the main landscapes units i.e. Cerro Prieto Mountain, Overall Piedmont and Zacándaro Piedmont, respectively.

5.1.1. Soils of Cerro Prieto landscape

The Cerro Prieto volcanic mountain landscape located in the north of the study area covers 3.3 km^2 (6.7% of the total area). The main relief types are the mountain ridges/incision complex and the volcanic cones. Slope facet complexes are the major landforms. Soils of are mainly formed from basalt, andesite and recent volcanic ash erupted from the Paricutín volcano. Main soils are the Dystric and Eutric Regosols, Leptosols, Mollic and Ochric Andosols. All the soils have andic properties a typical characteristic of volcanic soils.

5.1.2. Soils of the overall piedmont

Piedmont includes inclined surface lying at the foot of mountains or hills. The overall piedmont represents an inclined land below the highly elevated Tancítaro Peak. The total area occupied by this landscape unit is 16.3 km^2 (33.0% of the study area). This landscape unit is located in the northwest and central part of the study area. The main relief types include the volcanic cones, volcanic domes, horseshoe volcanoes, lava flow terraces and the accumulational/erosional terraces. Landforms are the slope-facet complexes, treads, risers and tread-riser complexes. The soils are formed from volcanic ash, pyroclastic deposits, lava flows, basalt and andesite. Major soil types include Eutric and Dystric

Regosols, Ochric, Vitric and Humic Andosols, Humic Cambisols as well as Chromic Luvisols. Like soils of the Cerro Prieto landscape, these soils also have characteristic andic properties.

5.1.3. Soils of the Zacándaro piedmont

The Zacándaro piedmont occupies the largest portion of the study area, which occupies 29.7 km^2 (60.3%). It is located in the southern part of the study area. The main relief types include the volcanic domes, and volcanic lava flow terraces. Main landforms include the tread-riser complexes, slope facet complex, treads and risers. Soils are formed from basalt, andesite and volcanic ash. Main soil types include Dystric Regosols, Ochric and Humic Andosols, Chromic Cambisols and Chromic Luvisols. These soils have also andic properties. Figure 5-1 shows the geo-pedological map of the Zacándaro sub-watershed and Table 5-1 the respective geo-pedological legend.

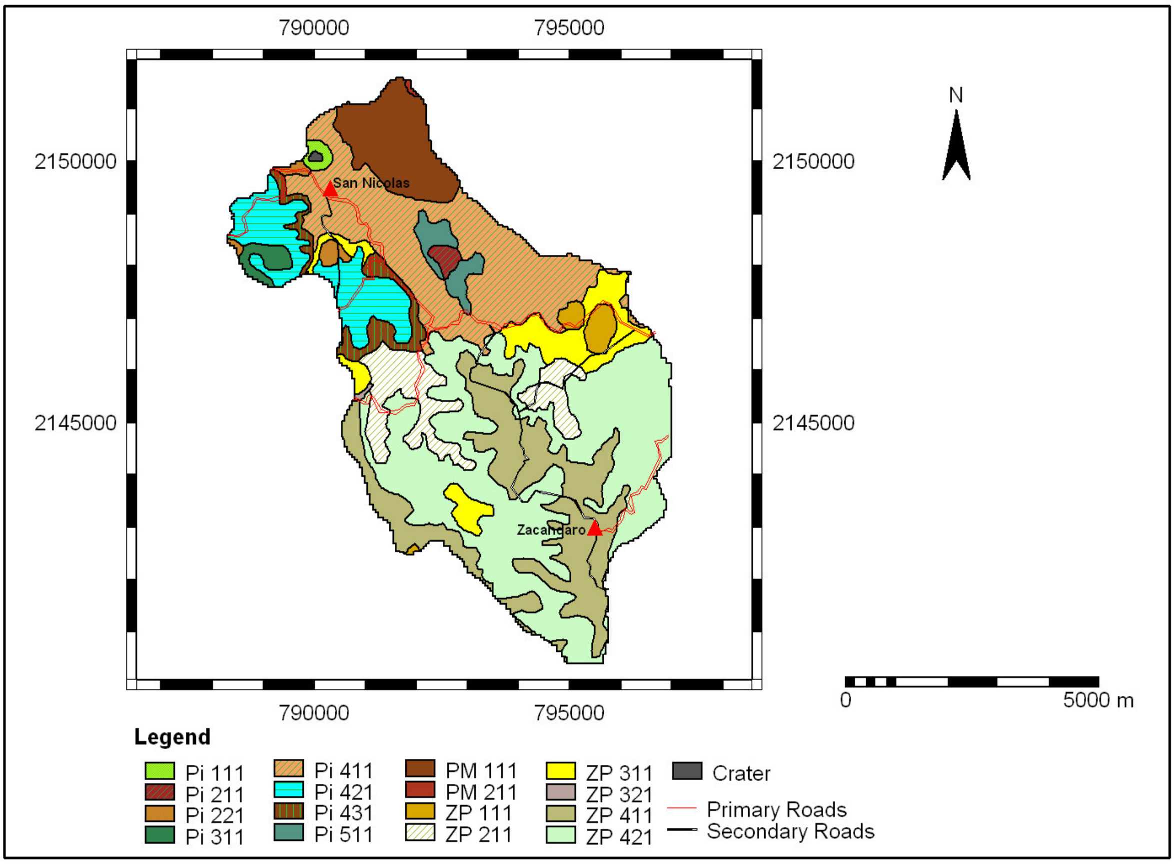


Figure 5-1 **The geo-pedological map of the Zacándaro sub-watershed**

Table 5-1 The geo-pedological legend of the Zacándaro sub-watershed

LANDSCAPE	RELIEFTYPE	LITHOLOGY	LANDFORM	MAP UNIT	SLOPE*	DOMINANT TAXA	AREA (%)
"Cerro Prieto" Volcanic Mountain (PM)	Ridges/Incisions Complex	Basalt, Andesite &Volcanic ash	Slope-Facet Complex	PM 111	07, 08	Dystric Regosols. Leptosols. Mollic and Ochric Andosols.	6.58
	Volcanic Cones	Basalt, Andesite & Volcanic ash	Slope-Facet Complex	PM 211	08, 09	Eutric Regosols. Leptosols. Mollic Andosols	0.07
Overall Piedmont (Pi)	Volcanic Cones	Cinder &Volcanic ash	Slope-Facet Complex	Pi 111	09, 10	Dystric Regosols. Ochric and Humic Andosols	0.52
	Volcanic Domes	Pyroclastic Deposits, Lava Flows & Volcanic ash	Slope-Facet Complex	Pi 211	08, 09	Ochric, Humic and Vitric Andosols. Dystric Regosols.	0.50
		Basalt, Andesite & Volcanic ash	Slope-Facet Complex	Pi 221	08, 09	Ochric and Humic Andosols. Leptosols. Humic Cambisols. Dystric Regosols.	0.77
	Horseshoe Volcano	Basalt, Andesite & Volcanic ash	Slope-Facet Complex	Pi 311	08, 09	Ochric and Humic Andosols. Leptosols. Dystric Regosols	0.96
	Lava Flow Terraces	Andesite, Basaltic Lava Flows & Volcanic ash	Tread/Riser Complex	Pi 411	06, 08	Ochric and Humic Andosols Leptosols	18.94
		Basalt, Andesite & Volcanic Ash	Tread	Pi 421	06, 08	Humic Cambisols. Humic and Ochric Andosols. Dystric Regosols	6.93
		Colluvio-alluvium	Riser	Pi 431	05, 06	Chromic Cambisols. Humic and Ochric Andosols. Chromic Luvisols	2.71
	Accumulational/Erosional Terraces	Colluvio-alluvium & Volcanic ash	Tread-Riser Complex	Pi 511	05, 06	Dystric Regosols. Ochric, Humic and Vitric Andosols.	1.73
"Zacándaro" Piedmont (ZP)	Volcanic Domes	Basalt, Andesite & Volcanic ash	Slope-Facet Complex	ZP 111	08, 09	Ochric and Humic Andosols	1.42
	High Lava Flow Terraces	Basalt, Andesite & Volcanic ash	Tread-Riser Complex	ZP 211	07, 08	Humic Andosols. Leptosols	6.50
	Mid Lava Flow Terraces	Basalt, Andesite & Volcanic ash	Tread	ZP 311	07, 08	Humic and Ochric Andosols. Leptosols.	6.00
		Colluvio-alluvium	Riser	ZP 321	08, 09	Humic and Ochric Andosols. Leptosols.	0.09
	Low Lava Flow Terraces	Basalt, Andesite & Volcanic ash	Tread	ZP 411	06, 08	Chromic Luvisols. Chromic Cambisols. Ochric Andosols	15.95
		Colluvio-alluvium	Riser	ZP 421	09, 10	Chromic Luvisols. Chromic Cambisols. Ochric Andosols	30.35
Total							100

Note: Slope classes are based on FAO (1990)

5.2. Results of soil moisture modelling

The results of soil water balance are monthly runoff, available soil moisture at the root depth and surplus moisture. These results are presented and discussed in the subsequent sections. The relationship between annual soil moisture storage and predicted annual soil erosion rates by RMMF is later discussed under the results of soil erosion modelling.

5.2.1. Surface runoff

Spatial distribution of annual surface runoff is shown in Figure 5-2. The average annual runoff over the entire catchment was estimated to be 150 mm yr^{-1}, with much of catchment found to have a range between 0-400 mm. In terms of different land uses, the highest runoff rate was found in the bare soil with an average of 518 mm yr^{-1} and the lowest in closed forest (90 mm yr^{-1}). With respect to other land use/ land cover types, the estimated annual runoff was 172 mm yr^{-1} for open forest, 236 mm yr^{-1} for annual crops, 145 mm yr^{-1} for perennial crops, 364 mm yr^{-1} for grassland and 327 mm yr^{-1} for shrubs. The observed differences may be attributed to different in infiltration rates, moisture storage capacity within the profile and initial moisture contents among soils under various land use/cover types.

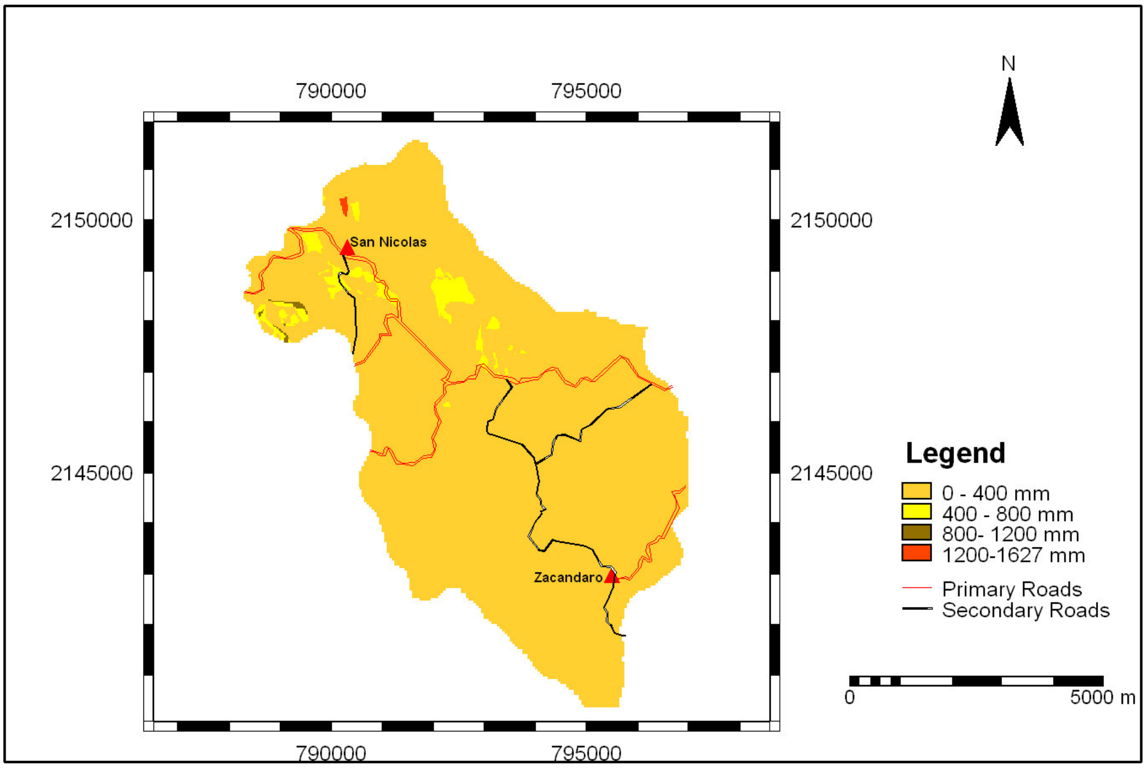


Figure 5-2 Spatial distribution of annual runoff in the Zacándaro sub-watershed

Monthly average runoff in relation to rainfall is indicated in Figure 5-3, while the monthly spatial distribution are given in Appendix 4. The pattern of mean monthly runoff clearly reflects the rainfall pattern in the study area. The average highest runoff (38 mm) is observed in July, which also coincides with highest average rainfall (380 mm) in the same month.

Annual total surface runoff was estimated by multiplying average annual surface runoff (150 mm yr^{-1}) by catchment area (49.25 km^2). Total sub-watershed output excluding the contribution of ground water runoff was found to be 7,414,086m^3yr^{-1}, which is comparable to the data on stream flow estimated from the Zacándaro sub-watershed (Fuentes, 2003, Personal communication). The annual stream flow at the Zacandaro outlet has been estimated at 7,329,164.9m^3yr^{-1}.

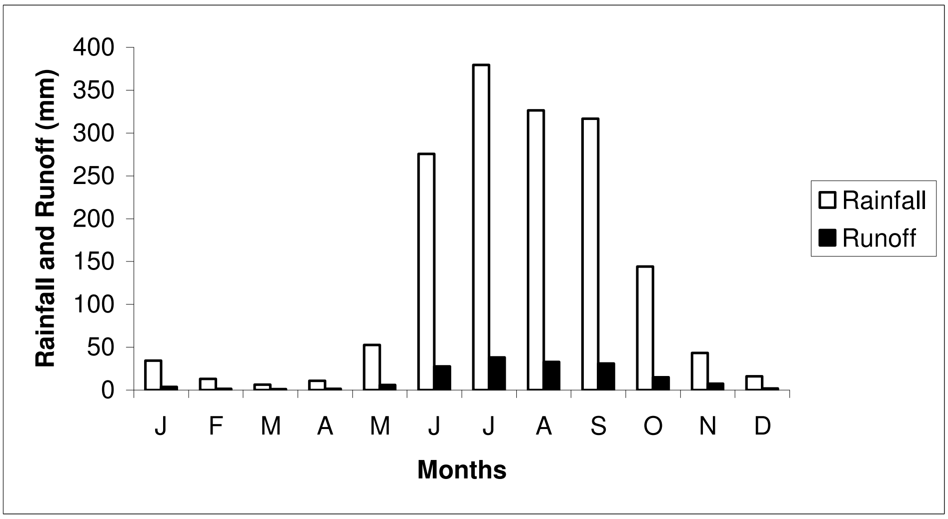


Figure 5-3 Mean monthly surface runoff and rainfall in the Zacándaro sub-watershed

5.2.2. Available soil moisture and its relationship to land use types

The spatial distribution of mean monthly soil moisture is shown in Figure 5-4. The average annual soil moisture over the entire catchment was estimated to be 240 mm yr^{-1}. Greater part of the catchment has average available soil moisture at the root depth ranging between 225 – 300 mm yr^{-1}. With respect to land use/cover types, the highest average available soil moisture of 304 mm yr^{-1} was estimated in open forest and the lowest of 82 mm yr^{-1} in bare soil. Mean annual available soil moisture in other land use/cover types was estimated at 292 mm yr^{-1} in closed forest, 123 mm yr^{-1} in annual crops, 201 mm yr^{-1} in perennial crops, 114 mm yr^{-1} in grassland and 100 mm yr^{-1} in shrubs. The variation in average available soil moisture is largely attributed to different land cover types and their interactions with soil texture. The variation is also due to the fact that amount of rainfall in the study area is closely related to elevation with highest rainfall in the upper part of the catchment and low rainfall in the lower part of the catchment.

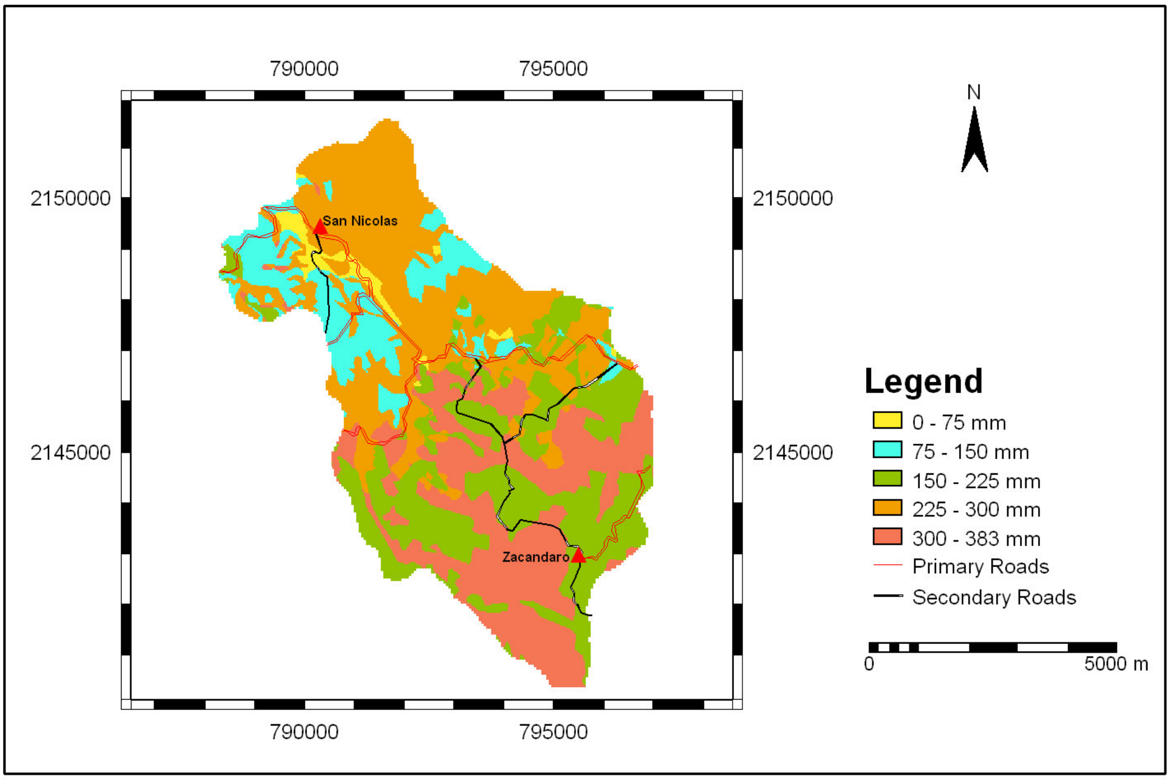


Figure 5-4 **Mean monthly soil moisture at the root depth in the Zacándaro sub-watershed**

Average monthly available soil moisture at the root depth is shown in Figure 5-5, while the monthly spatial distributions are given in Appendix 4. The results show that just after the end of rainy season (October), the moisture is withdrawn from the soil in order to satisfy the evapotranspiration demand that in general is higher than the rainfall in most part of the catchment. This continues until June when the rainfall is in excess and therefore starting to replenish the soil moisture. During the period from July to October the soil moisture is at the maximum water holding capacity and therefore excess rainfall contributes to excess soil moisture.

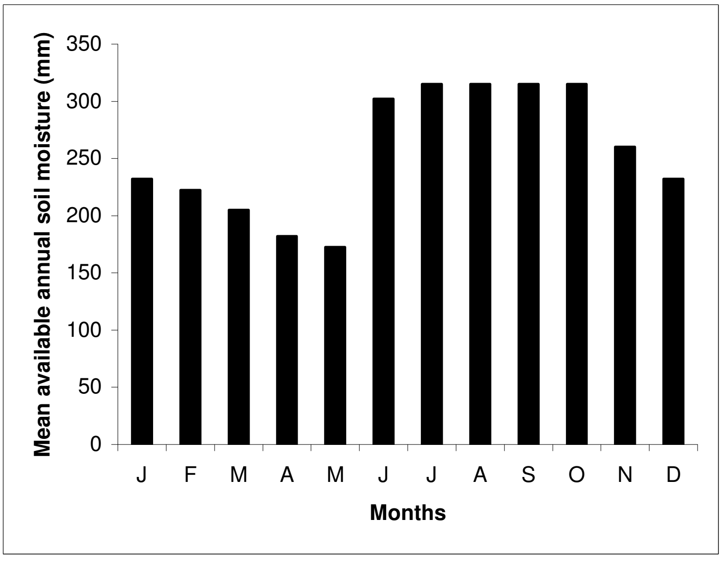


Figure 5-5 **Mean monthly soil moisture at the rooting depth in the Zacándaro sub-watershed**

The relationship between land cover and soil texture[2] (components that determine the available soil moisture) is shown in Table 5-2. Comparing the maximum available water holding capacity and the estimated mean annual available soil moisture at rooting depth, the results show a consistent pattern reflecting the interaction between land cover and soil texture, and their overall influence on soil moisture. Fitzjohn et al. (1998) have argued that since soil moisture is controlled by factors such as texture and vegetation among other factors, the spatial pattern of soil moisture will reflect the spatial distribution of these controlling factors. In terms of soil and water management, this further indicates that changes in land use/cover in an area could significantly affect the amount of water soil can store and indirectly influence the components of soil water balance especially runoff. Increased runoff in an area with no sufficient surface cover could result in more soil losses.

Figure 5-6, shows the relationship with a correlation coefficient of 0.9946 between the annual average available soil moisture at the rooting depth and the maximum water holding capacity. This is expected in area which receives excess rainfall as in the case of the study area. The average rain in the study area is estimated at about 1600 mmyr^{-1}, which is quite high.

Table 5-2 Relationship between land cover/soil texture and soil moisture

Land use_cover/texture	AWHC	Mean monthly soil moisture
Closed Forest_Loamy sand	250	232.8
Closed Forest_Sandy loam	300	282.8
Closed Forest_Sand_Sandy loam_Loamy sand	297	274.9
Closed Forest_Sand lom_Clay loam	385	343.9
Closed Forest_Loamy sand_Sand loam	290	281.7
Open Forest_Loamy sand	250	234.1
Open Forest_Sandy loam	300	270.2
Open Forest_Sand_Sand loam_Loamy sand	297	274.6
Open Forest_Sandy loam_Clay loam	385	340.4
Shrubs_Loamy sand	100	82.8
Shrubs_Sandy loam	150	130.8
Shrubs_Sand loam_Clay loam	235	193.1
Grassland_Loany sand	100	84.6
Grassland_Sandy loam	150	134.3
Grass land_Sand_Sandy loam_Loamy sand	147	130.7
Perennial crops_Loamy sand	150	123.4
Perennial Crops_Sand loam	250	221.3
Perennial crops_Sand_Sandy loam_Loamy sand	247	212.3
Perennial Crops_Sandy loam_Clay loam	235	196.7
Annual crops_Loamy sand	75	61.7
Annual crops_Sandy loam	150	139.3
Annual crops_Sandy loam_Clay loam	185	161.2
Annual crops_Loamy sand_Sandy loam	140	130.7
Bare soil_Loamy sand	100	82.3

[2] Soil texture in different horizons along the soil profiles as described in the field

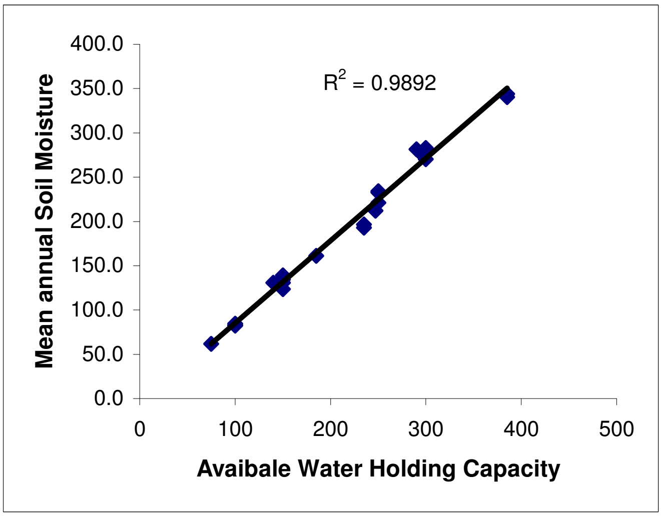


Figure 5-6 Relationship between maximum AWHC and predicted mean annual soil moisture

5.2.3. Excess Soil moisture

In this study the excess moisture was considered as the moisture that is in the excess of the available water holding capacity. The spatial distribution of the excess soil moisture is shown in Figure 5-7. Average annual excess soil moisture over the entire catchment was estimated at 918 mm yr^{-1} with greater portion of the catchment having total annual excess soil moisture varying between 700-1050 mm yr^{-1}. The highest excess soil moisture was estimated in the annual crops 1065.4 mm yr^{-1} with the lowest on bare soil (755 mm). Average excess soil moisture for closed forest was estimated at 981 mm yr^{-1}, for open forest 810 mm, for perennial crops 762 mm yr^{-1}, for grassland 843 mm yr^{-1} and for shrubs 826 mm yr^{-1}. The observed variation among different land use may be attributed to the dynamism of different components of water balance i.e. rainfall, runoff, evapotranspiration and soil storage which ultimately influences the excess moisture. The monthly distribution of the excess soil moisture is shown in Figure 5-8 while the monthly spatial distribution is given in Appendix 4. The significant excess soil moisture is realized from month of June to October (rainy season). Although in some of the months there are excess soil moisture it is important to note that only some parts of the catchment had excess soil moisture as indicated in monthly spatial distribution given in Appendix 4. For months of March and April no excess soil moisture was observed over the entire catchment as water is withdrawn from the soil moisture in order to satisfy the evapotranspiration demand of the atmosphere.

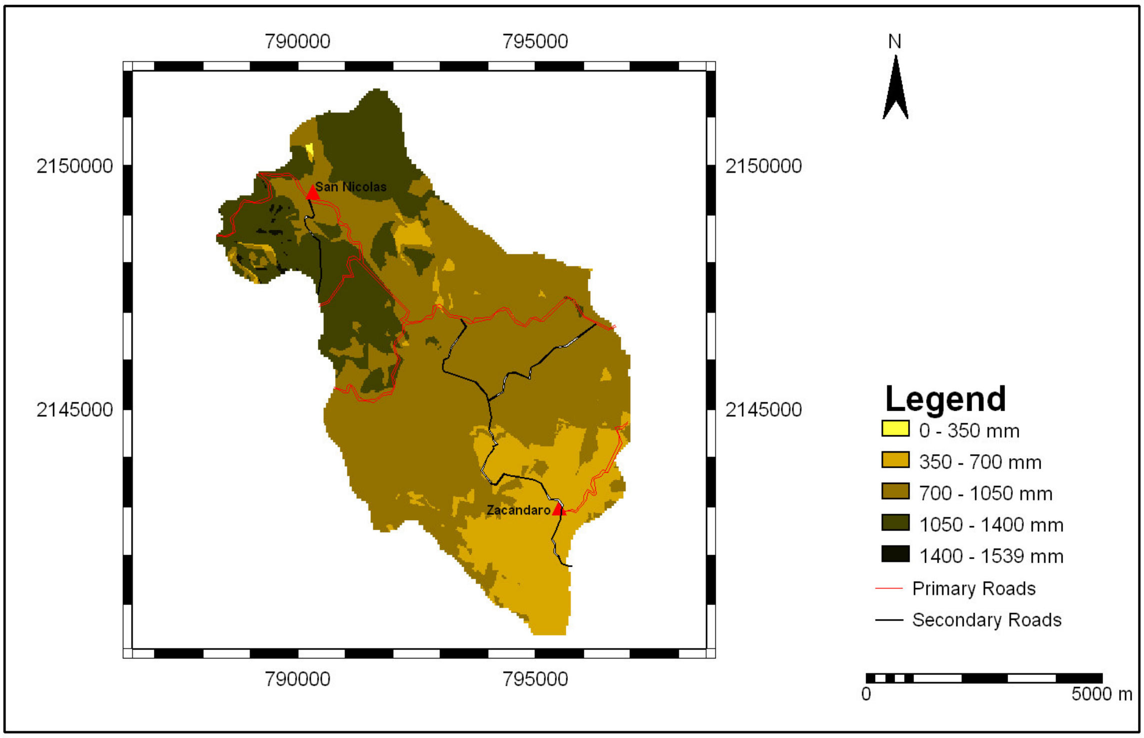


Figure 5-7 **Spatial distribution of total excess soil moisture in the Zacándaro sub-watershed**

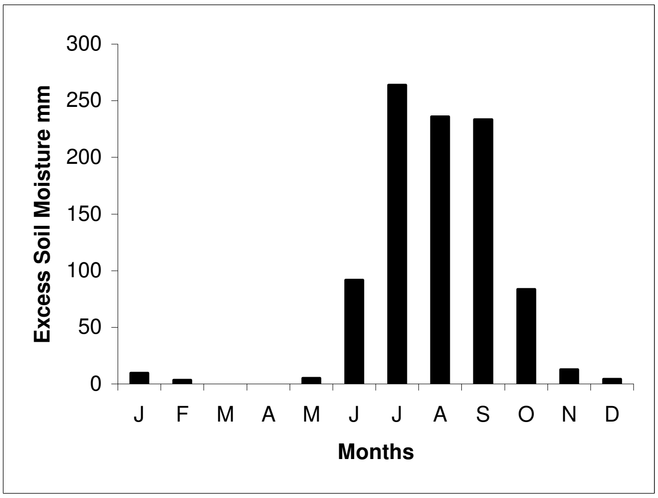


Figure 5-8 **Distribution of average monthly excess soil moisture**

5.3. Results of soil erosion modelling

This section presents the results of soil erosion modelling using the RMMF model. For each pixel in the image, two results were obtained i.e. the total annual soil detachment rate and the annual soil transport capacity rate. The lesser of the two values of soil transport capacity rate and soil detachment rate in the respective pixel was taken as the predicted annual soil erosion rate. The spatial distribution of the predicted annual soil loss rates in the Zacandaro sub-watershed is shown in Figure 5-9. The estimated annual soil loss rates were classified into five user defined severity classes i.e. no erosion (0-

1t ha^{-1} yr^{-1}), slight (1-5 t $ha^{-1}yr^{-1}$), moderate (5-10 t $ha^{-1}yr^{-1}$), severe (10-20 t $ha^{-1}yr^{-1}$) and very severe (>20 t $ha^{-1}yr^{-1}$). According to Morgan (1995), the appropriate measure of soil loss over which agriculturalists should be concerned is 10 t ha^{-1} yr^{-1}. This threshold was adopted as the soil loss tolerance limit in the Zacándaro sub-watershed, and was used as critical value for the separation of the moderate and severe annual soil erosion categories. Subsequent categorical distinctions were made at an increasing rate of classification (Millward and Mersey, 1999).

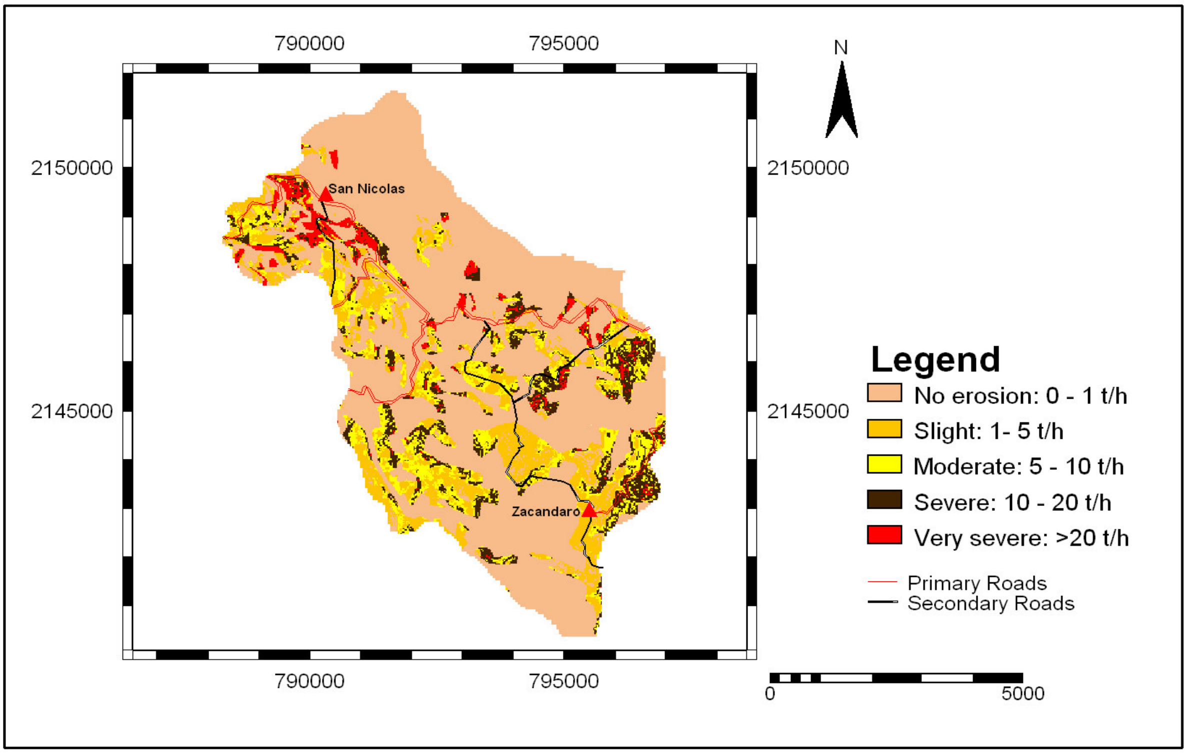


Figure 5-9 **Soil erosion hazard map in the Zacándaro sub-watershed**

The annual soil erosion predictions in the study area ranged from 0 to 138 t ha^{-1} yr^{-1} (pixel values). The average annual soil loss estimate per pixel was 22 t ha^{-1} yr^{-1} with a coefficient of variation of 97.5. High coefficient of variation is probably due to the heterogeneous nature of the study area in terms of topography and land use.

Proportion of each soil erosion hazard category was generated and area of each category computed. In terms of the overall erosion distribution, the maximum proportion 65% of the study area falls within the no soil loss hazard severity category, 15% was categorized as slight, 10 % as moderate, 8% as severe and 3% was classified as very severe (Figure 5-10). The results therefore indicate that the largest proportion of the study area (89%) is within the acceptable soil loss tolerance threshold of 10 t ha^{-1} yr^{-1} (Morgan, 1995). This appears to be quite acceptable base on the actual condition of the study area where a greater portion of land is still under natural vegetation. Exceptions to this in some areas are where annual and perennial cropping is currently being under taken where soil erosion rates are very high due to less protective cover.

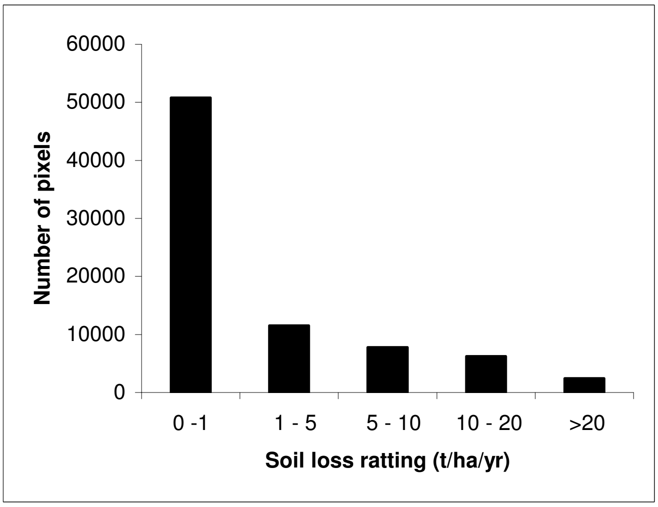


Figure 5-10 **Severity of soil erosion in the Zacándaro sub-watershed**

5.3.1. Soil erosion in relation to landscape

The results of the predicted soil erosion rates with respect to landscape units are shown in Table 5-3. Average soil loss rates of 0.25 t ha^{-1} yr^{-1} (with range varying from 0 to 0.7 t ha^{-1} yr^{-1}) were predicted for the Cerro Prieto landscape, 21 t ha^{-1} yr^{-1} (with range varying from 0-138 t ha^{-1} yr^{-1}) for the Overall Piedmont and 14 t $ha^{-1}yr^{-1}$ (with range varying from 0-68 t ha^{-1} yr^{-1}) for the Zacándaro Piedmont. It is important to note that the predicted soil erosion rates in the overall piedmont are quite high (21. t ha^{-1} yr^{-1}) compared to other landscape units, this may be attributed to the fact that annual crops are mainly grown in the overall piedmont, while forest and perennial crops occur in the Cerro Prieto and Zacándaro landscapes.

Table 5-3 **Predicted annual soil loss at a landscape level by RMMF**

Landscape	Area %	Average Detachment (t/ha/yr)	Average Transport Capacity (t/ha/yr)	Average soil loss (t/ha/yr	Std. Dev.
Overall Piedmont	33.0	39.0	7.5	21	23
Cerro Prieto Mountain	7.0	18.0	0.038	<1	0.2
Zacandaro Piedmont	60.0	38.0	3.4	14	10
Minimum		18.0	0.038	<1	
Maximum		39.0	7.5	21	
Mean		32.0	3.6	12	
CV%		37	102	90	

The results of the predicted annual soil erosion rates with respect to the mapping units are shown in Table 5-4. The average annual soil loss of 10 t ha^{-1} yr^{-1} with respect to different mapping units was predicted. The higher rates in some of the mapping units are attributed to interaction of different factors responsible for soil erosion. These factors include land cover, slope gradient as well as inherent soil properties. Comparing the detachability of these soils, almost all the mapping units have high detachability and the limiting factor being the transport capacity. Only one mapping unit (Pi311) has high transport capacity as compared to its soil detachment capacity.

Table 5-4 Predicted annual soil loss on different mapping units by RMMF

SMU	Area %	Average Detach-ment (t/ha/yr)	Average Transport Capacity (t/ha/yr)	Average soil loss (t/ha/yr	Std. Dev
Pi111	0.5	55.0	0.5	3	2.2
Pi211	0.50	42.0	0.2	1	0.7
Pi221	0.8	51.0	4.0	6	6.8
Pi311	1.0	35.0	69.0	25	26.0
Pi411	18.9	22.0	6.0	22	23.0
Pi421	6.9	51.0	4.0	7	5.0
Pi431	2.7	49.0	4.0	11	13.0
Pi511	1.7	95.0	13.0	17	26.0
PM111	6.6	18.0	0.04	<1	0.2
PM211	0.1	25.0	0.07	<1	0.03
ZP111	1.4	40.0	9.0	23	12.0
ZP211	6.5	39.0	3.7	10	6.3
ZP311	6.0	43.0	3.2	9	9.4
ZP321	0.1	38.0	0.0	0	0.0
ZP411	16.0	34.0	2.1	7	5.0
ZP421	30.3	36.0	3.9	12.	7.0
Minimum		18.0	0.0	0.	
Maximum		95.0	69.0	25	
Mean		42.1	7.7	9	
CV%		42	216	89	

With respect to the effect of slope gradient on predicted soil loss rate, four slope gradient categories were created according to FAO (1990) guidelines. These were gentle slopes (0-5%). moderate slopes (5-15%), steep slopes (15-30%) and very steep slopes (>30%). The results of average annual soil loss with respect to different slope categories are presented in Table 5-5. The results indicate an increase in soil losses although in moderate and steep slope categories the rates are almost similar. The highest rates (19 t ha^{-1} yr^{-1}) was predicted in the very steep slope category (>30%) and the lowest (10 t ha^{-1} yr^{-1}) in the gentle slope category (0-5%). On moderate (5-15%) and steep slopes categories (15-30%), the predictions were 15and 14t ha^{-1} yr^{-1} respectively. The increase of soil loss with increase in slope gradient especially when there is less surface protective cover is well documented (Morgan, 1995: Nearing et al., 1994). On steep slopes the detached particles can easily be transported down the slope once forces of transportation i.e. rainfall set in. The almost similar predicted soil loss rates for the moderate and steep slopes categories indicate that even with deferent slope gradients if the surface cover is adequate soil loss can be curtailed. This emphasizes the importance vegetation cover plays in steep slopes.

Table 5-5 Annual soil loss in different slope categories as predicted by RMMF

Slope class	Area %	Average Detachment (t/ha/yr)	Average Transport Capacity (t/ha/yr)	Average soil loss (t/ha/yr	Std. Dev.
Gentle	8.5	34.2	1.5	10	22.0
Moderate	27.8	35.0	3.0	15	21.4
Steep	29.0	35.0	4.3	14	13.0
Very steep	34.9	37.0	6.6	19	15.0
Minimum		34.2	1.5	10	
Maximum		37.0	6.6	19	
Mean		35.3	3.9	14	
CV%		3.3	56	25	

5.3.2. Soil erosion in relation to land use/land cover

Determining soil erosion rates and associated land use/ land cover types helps in understanding the efforts needed to save the physical quality of land and ultimately holds valuable information for developing necessary conservation strategies. Table 5-6 shows the categorization of RMMF average annual soil loss rates with respect to land use/ land cover types. Histograms showing pixel distributions in open forest, annual crops, perennial crops, grassland and shrubs are shown in Figures 5-11 to 5-15. These distributions show a right-skewed distribution of predicted annual soil losses.

Table 5-6 Predicted annual soil loss by RMMF model in different land use/ land cover classes

Land use	Area %	Average soil loss (t/ha/yr	Std. Dev
Closed Forest	51.6	1	1.4
Open Forest	8.2	1	0.9
Annual Crops	11.2	18	15.0
Perennial crops	26.3	16	14.0
Grassland	1.3	4	3.7
Shrubs	1.2	<1	0.2
Bare Soil	0.1	122	23.0
Minimum		<1	
Maximum		122	
Mean		23.2	
CV (%)		190	

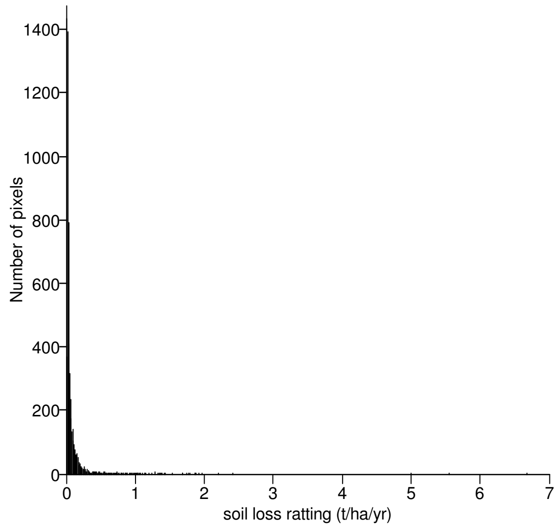


Figure 5-11 Pixel distribution in open forest

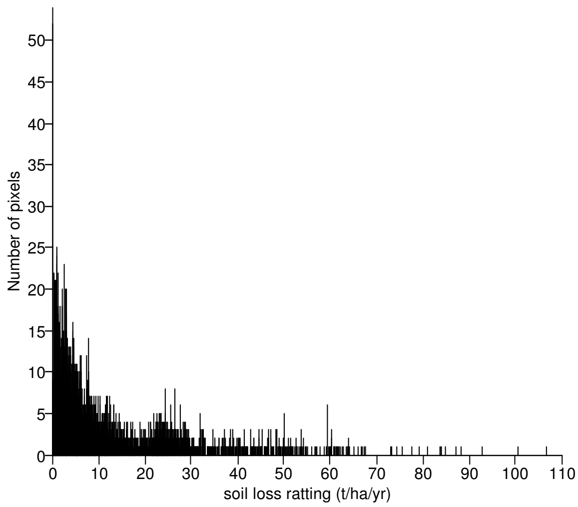


Figure5-12 Pixel distribution in annual crops

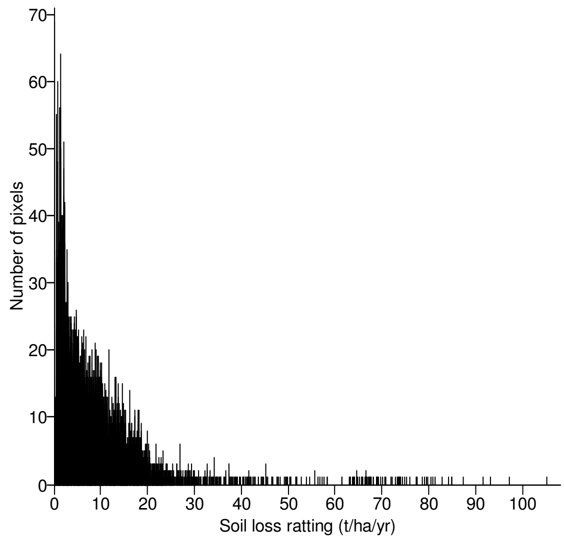


Figure 5-13 Pixel distribution in perennial crops

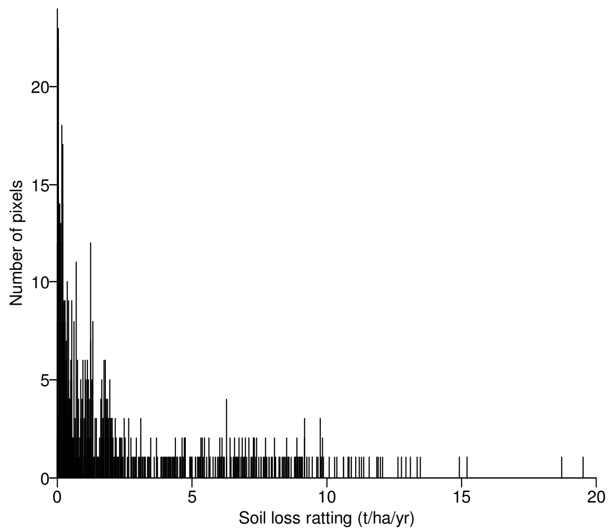


Figure 5-14 Pixel distribution in grassland

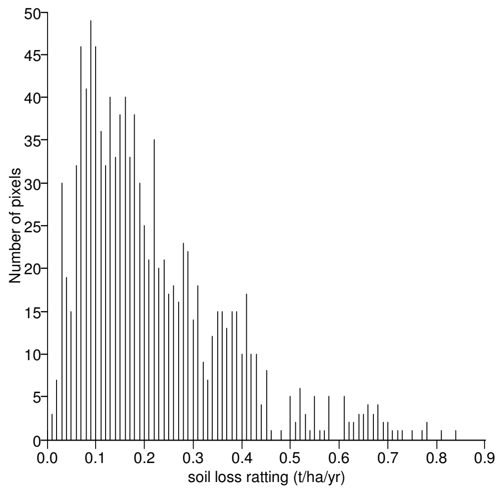


Figure 5-15 Pixel distribution in shrubs

The results show variation in predicted average annual soil loss under different land use types, with the greatest soil loss (122 t ha^{-1} yr^{-1}) predicted in the bare soil and lowest for shrubs (<14 t ha^{-1} yr^{-1}). Predicted annual soil erosion rates for other land use categories were 1t ha^{-1} yr^{-1} for closed forest, 1 t ha^{-1} yr^{-1} for the open forest, 18 t ha^{-1} yr^{-1} for annual crops (maize), 15.5 t ha^{-1} yr^{-1} for perennial crops and 4.2 t ha^{-1} yr^{-1} for the grassland (Table 5-6). The higher values recorded in the bare soils may be attributed to the lack of protective cover and the fact that the area previously was under annual crops and was abandoned after it was no longer suitable for agricultural production. This is in line with the fact that Andosols become very erodible when intensively cropped or overgrazed (Nishimura et al., 1993). Other studies have also shown the occurrence of high soil loss rates in Andosols (Poulenard et al., 2001; Basher and Ross, 2002) and this is particularly so after drying of soil surface. The observed higher rates of soil loss in annual crops have been demonstrated in several studies (Renschler, 1996; Shrestha, 1997). The greater rates of soil losses are due to the relatively short vegetation cover of annual crops and the fact that after harvesting, especially in the study area, the crop residues are also used to feed the animals. In addition to this, the repeated soil disturbance arising from tillage and weeding operations may also intensify the problem. It is also possible that the use of mouldboard plowing may create a plow pan just below the soil surface and hence limit the rate of infiltration. The reduced infiltration could result in the increased surface runoff and hence accelerated soil erosion

Higher soil loss rates in the perennial crops may be attributed to the different management practices employed within the individual farms as well as stage of plant growth. Management practices in general involves slashing of vegetation under the trees in most farms while in other it involves clear weeding leaving the soil under the trees unprotected. It is in these areas where erosion rates are high. High erosion rates may also be attributed to the newly established farms where the protective natural vegetation is removed. On the other hand, the low soil loss predicted in other land use types can be attributed to the protective cover factor in these land uses. Moreover, trees, grasses and shrubs have a high sediment trapping efficiency, which traps soil particles on the flow path of erosion (Anton et al., 2002), thus significantly curtailing soil losses.

Tiscareńo-López et al. (1999) have presented some results from the Patzcuaro watershed, which is close to the study area. The general characteristics of the watershed include average rainfall amounting to about 1000 mm per year and soil characterised as course loamy Andosols. These characteristics clearly reflect those of the Zacándaro sub-watershed. In their study, they reported annual erosion rates of 3 t ha^{-1} yr $^{1-}$in maize plots under conventional tillage on an 8% slope. At the watershed scale, soil losses under conventional tillage were 16 t ha^{-1} yr^{-1}. Comparing the results obtained with the prediction using the RMMF it appears that the predicted rates are within those reported by Tiscareño-López et al. (1999) in which an average of 18 t h^{-1} yr^{-1} in annual crops was predicted.

5.3.3. Relationship between soil loss rates and soil moisture

To have an insight with respect to the relationship between the estimated average annual available soil moisture at the rooting depth and the predicted annual soil erosion rates using RMMF, a correlation on pixel-by-pixel basis was performed. A list consisting of mean annual available soil moisture and annual soil loss was created and correlation coefficient calculated. A modest correlation coefficient of –44 was obtained indicating that the higher the soil loss in a given pixel the lower the amount of average annual soil moisture at the rooting depth. This is in line with earlier studies on mineral soils which have shown that the limited capacity of soil moisture storage as a possible cause of erosion (Van Dijk and Kwaad, 1996; Martinez-Mena et al., 1998). In addition, soil moisture has also been reported to be a key factor in determining the surface runoff response to a given precipitation event (Fitzjohn et al., 1998)

5.4. Simple field tests results and their relation to results from the RMMF model

Soil erodibility was assessed by a number of simple field tests that included dry crumb, manipulation, rainfall acceptance, pinhole and shear vane tests. From the results of simple field tests, the availability of erodible material, resistance to scour of the top soil, overland flow production and the inter-rill and rill erodibility were assessed. The results of inter-rill and rill erodibility were combined and resulted into a qualitative soil erosion hazard classes.

5.4.1. Availability of erodible materials

The results of weighted rank of crumb and manipulation tests are shown in Table 5-7. In general, the availability of erodible materials in the study area varies between and within the landscape units. The overall hazard classes obtained from combination of the weighted ranks of crumb and manipulation tests indicate that all the soils have moderate to high availability of erodible material. This is largely due to higher ranking of the manipulation test. Apart from the fact that individual aggregates are stable, but the cohesion forces among the aggregates is very low and hence resulting in more erodible material.

Table 5-7 Availability of erodible materials

SMU	No of observations	Crumb Test	Weighted	Manipulation	Weighted Sum	Weighted Rank	Hazard Class
Pi111	3	1	2	6	8	3	M
Pi211	3	1	2	6	8	3	M
Pi221	3	1	2	6	8	3	M
Pi311	3	2	4	6	10	4	H
Pi411	3	2	4	6	10	4	H
Pi421	3	2	4	6	10	4	H
Pi431	3	2	4	6	10	4	H
Pi511	3	2	4	6	10	4	H
PM111	3	2	4	6	10	4	H
PM211	3	2	4	6	10	4	H
ZP111	3	2	4	3	7	3	M
ZP211	3	1	2	6	8	3	M
ZP311	3	1	2	6	8	3	M
ZP321	3	1	2	6	8	3	M
ZP411	3	2	4	6	10	4	H
ZP421	3	1	2	5	7	3	M

The observed aggregate stability was also assessed with respect to organic matter content. The soils were found to have varying organic matter contents varying between 1-24% that could partially contribute to the observed structural stability and low ratting of crumb test. Additionally, soils formed from volcanic materials have also been reported to have high structural stability due to the presence of allophanes and other amorphous compounds (Tan, 1984; Maeda and Soma, 1985). The presence of such components in the soils of the study area may also explain the observed aggregate stability.

Using the Pearson's Product Moment Correlation, the dry crumb test shows negative correlation with the organic matter content of the soil with r-value being –0.47, which indicates that the higher the organic matter contents the lower the crumb test rating. However, this relation is not very strong (r^2 value of 0.20), which means that 80% of the observed aggregate stability is accounted by other factors apart from organic matter. The contribution of clay contents in aggregate stability is very minimal as the soils have very low clay content Table 5-8.

Table 5-8 Records of crumb tests, clay content and organic matter

SMU	No. of observations.	Crumb test results	%Clay	%OM
Pi111	3	1	6	7
Pi211	3	1	7	24
Pi221	3	1	6	7
Pi231	3	2	3	3
Pi311	3	2	4	7
Pi411	3	2	8	9
Pi431	3	2	10	12
Pi511	3	2	1	1
PM111	3	2	1	1
PM211	3	2	1	1
ZP111	3	2	7	14
ZP211	3	1	6	9
ZP311	3	1	8	13
ZP321	3	1	8	13
ZP411	3	2	10	10
ZP421	3	1	16	9

5.4.2. Overland flow production

The results of the ranking of the infiltration or rainfall acceptance test are shown in Table 5-9. The infiltration rates are quite high as compared to other mineral soils. Moisture present in the soils during the fieldwork could have modified the relative high overland flow production. Initial moisture greatly influences the rate of infiltration into the profile. The examples of typical infiltration curves are indicated in Figures.5-16 & 5-17.

Table 5-9 Ranks for overland flow production

SMU	No of observations	Rainfall acceptance cm/hr	Rank	Hazard *Class
Pi111	3	7.8	5	VH
Pi211	3	63.1	1	VL
Pi221	3	7.8	5	VH
Pi311	3	41.2	3	L
Pi411	3	9.5	5	VH
Pi421	3	8.0	5	VH
Pi431	3	10.5	5	VH
Pi511	3	18.2	4	H
PM111	3	6.6	5	VH
PM211	3	6.6	5	VH
ZP111	3	20.5	4	H
ZP211	3	5.4	5	VH
ZP311	3	18.5	4	H
ZP321	3	18.5	4	H
ZP411	3	22.4	4	H
ZP421	3	27.3	4	H

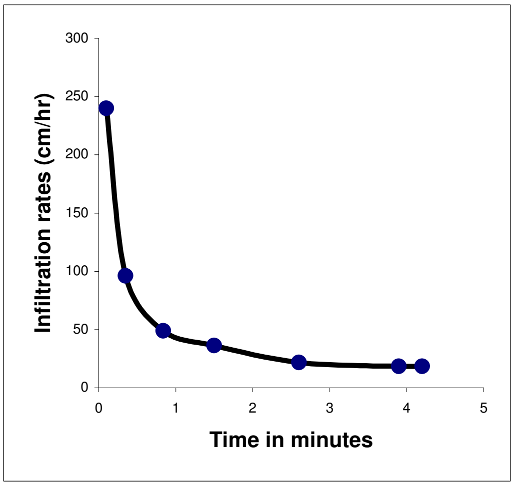


Figure 5-16 Infiltration curve from ZP311

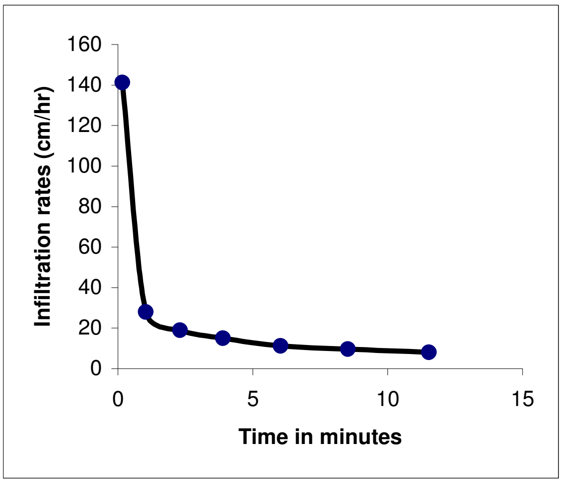


Figure 5-17 Infiltration curve from Pi421

5.4.3. Resistance to scour

The results of pinhole and shear vane tests which indicate resistance to scour are presented in Table 5.10. The overall results show that resistance to scour varies from low to high, with much of the study area being rated as moderate. It appears that the sandy nature of soils contributes significantly to the observed resistance to scour. Results of the particle size distribution analysis shows that all sample have high sand contents, followed by silt which shows that soil textural classes are likely to promote erodibility.

Table 5-10 Ranks for resistance to scour

SMU	No of Observa-tions	Pinhole rating	Rank	Shear vane (kPa)	Rank	Sum of ranks	Rank of the sum of ranks	Hazard Class*
Pi111	3	4	4	3.4	1	5	3	M
Pi211	3	2	2	1.9	3	5	3	M
Pi221	3	4	4	3.4	1	5	3	M
Pi311	3	4	4	2.8	1	5	3	M
Pi411	3	4	4	3.3	1	5	3	M
Pi421	3	4	4	1.2	4	8	4	H
Pi431	3	4	4	1.8	3	7	4	H
Pi511	3	4	4	1.4	4	8	4	H
PM111	3	4	4	2.7	2	6	3	M
PM211	3	4	4	2.7	2	6	3	M
ZP111	3	2	2	3.2	1	3	2	L
ZP211	3	4	4	3.5	1	5	3	M
ZP311	3	3	3	1.8	3	6	3	M
ZP321	3	3	3	1.8	3	6	3	M
ZP411	3	3	3	2.5	2	5	3	M
ZP421	3	3	3	2.9	1	4	2	L

5.4.4. Inter-rill and rill erodibility

Inter-rill erosion is the removal of the uniform thin layer of the soil surface by sheet wash. On the other hand Rillibility is the sensitivity of soil to rill formation. The results of inter-rill and rill erodibility assessment by simple field tests are presented in Table 5-11. The sum of ranks between the rill and inter-rill erodibility was classified into four general erodibility classes. These were very low (1-2), low (3-4), moderate (5-6) and high (7-8). The overall results show that the susceptibility to inter-rill and rill erodibility lies between very low and high with the high and moderate being the dominant classes. However, it should be noted that these tests alone cannot give the overall picture of the soil erodibility, other factors that are necessary for soil erosion should also be considered. At this juncture it is safe to say that the simple field tests are useful in providing an indication of the susceptibility of different soils to erosion.

Table 5-11 Ranks for inter-rill and rill erodibility

SMU	Material Availability Ranks *(A)	Overland flow Ranks*(B)	Resistance to Scour Ranks * (C)	Inter rill Erodibility *AB	Ranks	Rillibility *BC	Ranks	Sum of ranks	Final Ranks	Hazard Class
Pi111	3	5	3	3	3	3	3	6	3	M
Pi211	3	1	3	1	1	1	1	2	1	VL
Pi221	3	5	3	3	3	3	3	6	3	M
Pi311	4	3	3	3	3	3	3	6	3	M
Pi411	4	5	3	4	4	3	3	7	4	H
Pi421	4	5	4	4	4	4	4	8	4	H
Pi431	4	5	4	4	4	4	4	8	4	H
Pi511	4	4	4	4	4	4	4	8	4	H
PM111	4	5	3	4	4	3	3	7	4	H
PM211	4	5	3	4	4	3	3	7	4	H
ZP111	3	4	2	3	3	2	2	5	3	M
ZP211	3	5	3	3	3	3	3	6	3	M
ZP311	3	4	3	3	3	3	3	6	3	M
ZP321	3	4	3	3	3	3	3	6	3	H
ZP411	4	4	3	4	4	3	3	7	4	H
ZP421	3	4	2	3	3	2	2	5	3	M

5.4.5. Relationship between results of simple field tests and predicted soil erosion rates using RMMF

Simple field tests have been developed as an alternative to expensive methods of assessing soil erodibility (Bergsma, 1990). These tests are considered to provide an index of aspects of soil erodibility and are meant to be used in survey of soil erodibility and soil erosion hazards. Table 5-12, shows the results of overall susceptibility to inter-rill and rill erodibility in relation to RMMF model severity classes, soil detachment and annual soil loss rates in different mapping units. The results of simple field tests indicate that the soils in terms of susceptibility to inter-rill and rill erodibility range between very low and high. Comparing these results with the annual detachment rate it appears that the soils of the study area are quite susceptible to detachment although the overall soil erosion depends on the transport capacity, which is very low in all the mapping units (Table 5-4). Comparing these results with the predicted annual soil erosion rates computed as the minimum between the transport capacity and detachment, the following deductions can be made:-

- Though not consistent in all mapping units, the simple field tests have resulted to fairly similar results as those predicted by the RMMF model. This can be exemplified in mapping units Pi211, Pi431, Pi511, ZP211 and ZP311. Comparing with the user defined classes i.e. no erosion (0-1 t ha^{-1} yr^{-1}), slight (1-5 t ha^{-1} yr^{-1}), moderate (5-10 t ha^{-1} yr^{-1}), severe (10-20 t ha^{-1} yr^{-1}) and very severe (>20 t ha^{-1} yr^{-1}), there is still a fare prediction although there is a slight shift in some of the classes determined by these two approaches.
- The lack of consistency between the simple field-tests results and RMMF model results may be attributed to the fact that the simple fields tests results are point based and are extrapolated to a whole mapping unit. Comparison of point derived results and spatially derived results could lead to the observed inconsistency. The limitations of extrapolating point-derived data to a wider landscape have been pointed out by many researchers (Evans, 1993a; 1995a; Boardman, 1996; Herweg, 1996). They have argued that point derived data indicate only the magnitude of soil loss at a particular area, which is confined and excluded from interaction with its surroundings. Further, they pointed out that extrapolating point based results to larger spatial scales can be misleading because erosion rates may be varying due to variations in rainfall energy, gradient and length of slopes, inherent soil characteristics affecting erodibility and land use and land management practices.

Table 5-12 Comparison between simple field tests and RMMF derived results

SMU	Inter-rill and rill erodibility classes	RMMF severity classes	Average Detachment (t/ha/yr)	Annual soil loss (t ha^{-1} yr^{-1})
Pi111	M	Slight	55.0	2.6
Pi211	VL	No erosion	42.0	0.7
Pi221	M	Moderate	51.0	5.9
Pi311	M	Very severe	35.0	25.4
Pi411	H	Very severe	22.0	21.6
Pi421	H	Moderate	51.0	7.1
Pi431	H	Severe	49.0	11.0
Pi511	H	Severe	95.0	17.1
PM111	H	No erosion	18.0	0.3
PM211	H	No erosion	25.0	0.1
ZP111	M	Severe	40.0	22.5
ZP211	M	Moderate	39.0	9.50
ZP311	M	Moderate	43.0	8.5
ZP321	H	No erosion	38.0	0.0
ZP411	H	Moderate	34.0	6.9
ZP421	M	Severe	36.0	11.6

5.4.6. Relationship between results of semi quantitative soil erosion assessment and predicted soil erosion rates

In an attempt to evaluate the performance of the model, the semi quantitative assessment of soil erosion was carried out as described in section 4.11. Due to time limitation, semi quantitative assessment was carried out only on seven sites. Table 5-13 shows the calculated erosion indices and predicted soil erosion rates in the respective points. The results show that in areas where the predicted soil erosion rates are high also the soil erosion indices are high. To asses this relationship, a Pearson's Product Moment Correlation was calculated which resulted to a correlation coefficient of 0.9028. This indicates qualitatively, the RMMF has been able to predict and identify areas with different soil loss quite successfully. However, these results should be considered as indicative and not conclusive due to limited number of points used in this analysis.

Table 5-13 Results of semi quantitative soil erosion assessment

X Coordinates	Y Coordinates	Soil erosion indices	Erosion rates (t/ha/yr)	Land use/cover
790580	2150442	4.3	0.01	Closed Forest
790490	2150275	23.3	71.3	Bare Soil
790439	2149354	6	0.07	Grassland
789228	2149209	16	22.6	Annual crops
789292	2149173	15	10.6	Annual crops
790458	2149151	3.7	0.09	Open Forest
790458	2149151	5.7	1.14	Annual crops

5.5. Sensitivity of model parameters

Sensitivity analysis has been used in several studies (Renschler, 1996; Kadupitya, 2002; Yazidhi, 2003) to evaluate the stability of models to parameter change. In this study, input parameters namely slope gradient, rainfall amount and moisture storage capacity of the surface soil were considered. These parameters are directly or indirectly related to the transport capacity of the soils and were selected on the basis that any factor that will trigger the transport capacity will significantly affect the erosion rates. Preliminary analysis of the model sensitivity to the parameters related to the detachment such as surface cover indicated that, although there was a considerable increase in the soil detachment, the overall soil erosion was not affected. This was attributed to the limited transport capacity and the two-tie structure of the model, which takes the minimum between the detachment and transport capacity as the predicted soil erosion rates. The initial parameters were changed by magnitude of 5, 10, 15, 20 and 50% and the model was re-run using the changed values in one parameter at a time while retaining original values for other parameters. These values were selected to evaluate whether there could be a detectable trend in sensitivities of the RMMF model with small, medium and large shift in the original values.

5.5.1. Sensitivity of model to slope gradient

Although the slope factor under normal circumstance remains stable, it was considered important in sensitivity analysis to understand the behaviour of the model. It is an important parameter as it influences the soil detachment by runoff as well as the transport capacity of the runoff. Table 5-14 shows the sensitivity of soil loss to changes in slope gradient and graphically presented in Figure 18. The results shows that there was almost a constant response to changes in soil erosion rates as the slope gradient was being changed by the respective proportions. The results also show a relatively higher variability as indicated by the coefficient of variations. These high coefficients of variation values indicate that the response of soil loss to shifts in input parameters was highly variable across the landscape. To have an insight on the influence of surface cover on the observed responses of soil erosion to change in slope gradient, the output map were crossed with the surface cover map. The results showed that pixels with minimum surface cover were highly sensitive to change in slope gradient compared to those pixels that had more surface cover values. This was not unexpected owing to the fact that regardless of slope steepness, soil erosion rates are insignificant so long as there is reasonable surface cover.

Table 5-14 Sensitivity of RMMF model to slope gradient

Change in slope (%)	Change in soil loss (%)	Average estimated soil loss (t/ha/yr)	Coefficient of Variation
5	1.9	22.0	97.2
10	3.5	22.3	96.4
15	5.3	22.7	95.7
20	7.1	23.1	94.9
50	15.6	24.9	91.6

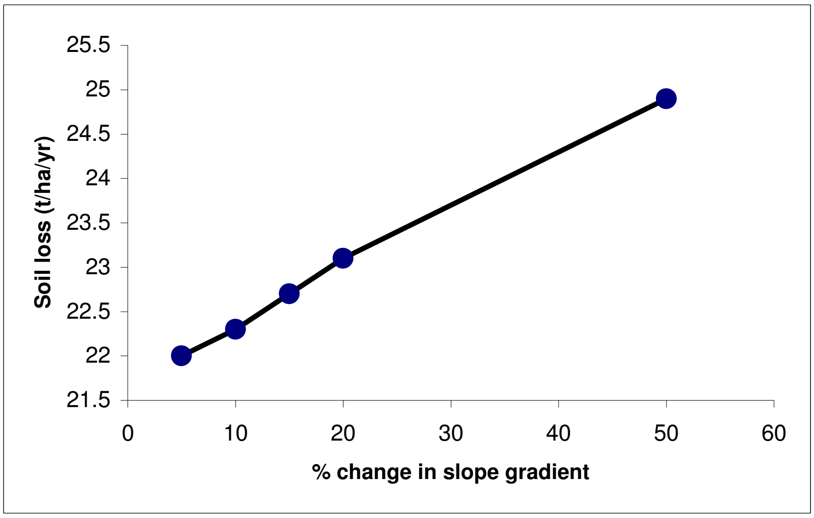


Figure 5-18 Sensitivity of RMMF model to slope gradient

5.5.2. Sensitivity of RMMF model to rainfall amount

Rainfall amount is an important component in many parameters of the RMMF model as one parameter affected by rainfall also influences the other. These parameters include the effective rainfall, leaf drainage, direct throughfall, kinetic energy of the direct throughfall, runoff volume, particle detachment by runoff as well as the transport capacity of the runoff. The effect of change in rainfall amount on the predicted soil loss rates is presented in Table 5-15 and graphically in Figure 19 . The results shows that when the rainfall was changed between 5 and 20% a more less linear trend was observed, however when the rainfall was changed by 50% there was an abrupt shift in soil loss rates amounting to more than 100%. This shift may be attributed to the increased detachment and more to it the transport capacity of the runoff. It has been indicated in section 5.3.1 that the major limiting factor with respect to soil erosion rates in the soil of the study area is the transport capacity. It is in this respect that any factor that could lead to the increase in transport capacity of the runoff could significantly result to soil erosion. These observations are further in line with those made by Wischmeier and Smith (1978), who observed that when other factors other than the rainfall are constant, soil losses are directly proportional to the rainfall parameter.

Table 5-15 Sensitivity of RMMF model to rainfall amount

Change in rainfall amount (%)	Change in mean annual rainfall	Change in soil loss (%)	Average estimated soil loss (t/ha/yr)	Coefficient of Variation
0	1600	0	21.5	97.5
5	1680	3.1	22.2	92.4
10	1760	15.6	24.9	87.1
15	1840	27.6	27.5	83.7
20	1920	39.7	30.1	82.7
50	2400	110.2	45.3	80.4

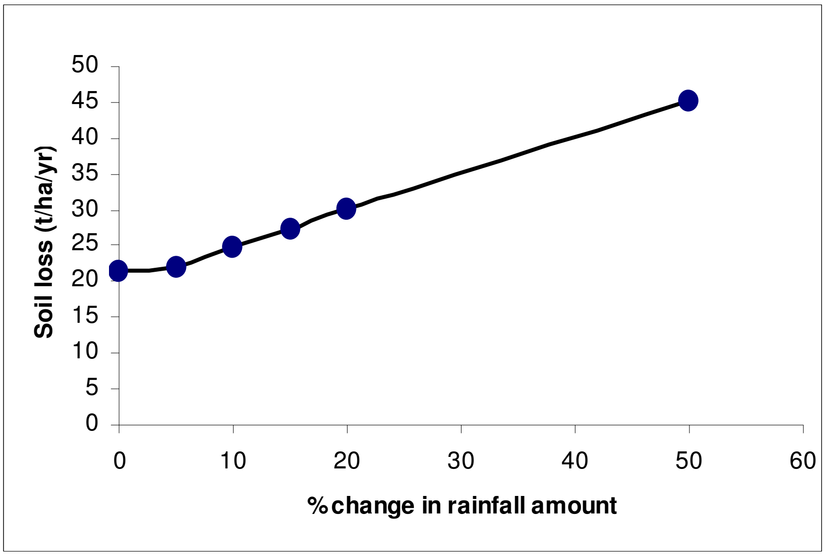


Figure 5-19 Sensitivity of RMMF model to rainfall amount

5.5.3. Sensitivity of RMMF to moisture storage of surface soils

Soil moisture storage have a direct influence on the amount of runoff generated which also in turn affect the detachment by runoff and transport capacity of the runoff. In the present study the moisture storage capacity was reduced by 5, 10, 15, 20 and 50%, respectively. The effect of change in moisture storage capacity on the predicted soil erosion rates is shown in Table 5-16 and graphically in Figure 20 .

The results shows that there was almost equal proportion in changes in predicted soil erosion rates with respect to change in soil moisture storage capacity. This indicates that these two parameters are negatively correlated i.e. the higher the soil moisture storage capacity the lower the soil erosion. This is inline with earlier findings on mineral soils that have shown that the limited capacity of soil moisture storage as a possible cause of erosion (Van Dijk and Kwaad, 1996; Martinez-Mena et al., 1998).

Table 5-16 Sensitivity of RMMF model to soil moisture storage capacity

Change in moisture storage (%)	Change in soil loss (%)	Average estimated soil loss (t/ha/yr)	Coefficient of Variation
5	5.2	22.7	95.6
10	11.2	23.9	85.8
15	17.8	25.4	80.4
20	24.8	26.9	76.2
50	45.0	31.4	66.3

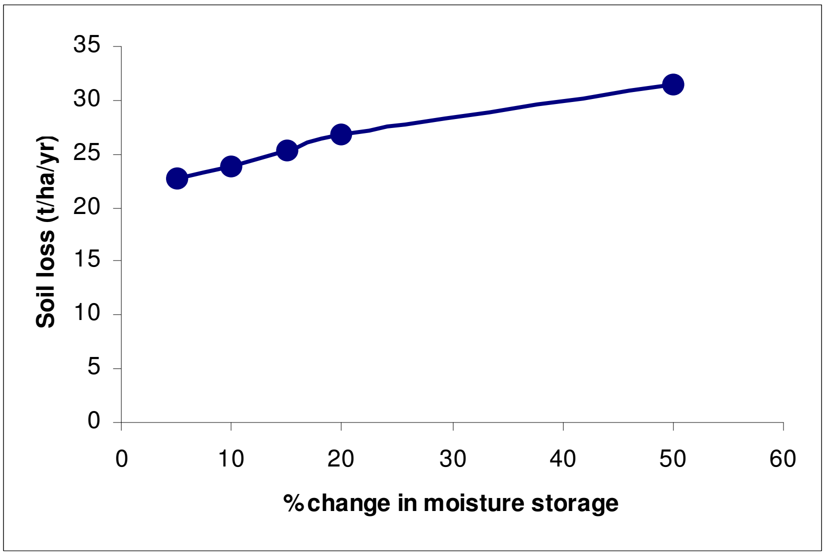


Figure 5-20 Sensitivity of RMMF model to soil moisture storage capacity

5.5.4. Models performance

From the practical point of view, the accuracy of the model can only be validated with another set of quantified data from the same area where the model was applied. This kind of data set was not available in the study. To try to overcome this limitation, a variety of techniques were employed to evaluate the performance of the model. These techniques included the comparison of predicted soil erosion rates from the RMMF model and data from the Patzcuaro watershed based on experimental plots and other model results, simple field tests and semi-quantitative assessment of soil erosion features.

Comparison of RMMF model outputs with data from the Patzcuaro watershed as discussed in section 5.3.2 has shown that the predicted soil erosion rates are within the experimental plot results and other soil erosion prediction model results. When the model results were compared with the results of the simple field test, there was some resemblance between erosion hazard classes generated using simple field tests and the model outputs. The lack of consistency may largely be attributed to the inherent limitation in extrapolating point data (simple filed tests) to a wide landscape.

To have an insight on the ability of the model to identify areas with different rates of soil erosion, a simple field test as discussed in section 5.3.6 was used. Although the number of points used was small, however this technique has provided an indication of the predictive capabilities of RMMF. From above it can be concluded that although the used techniques are not mathematically rigorous, but have provided an independent means to corroborate the success of model at predicting locations with consequential soil loss potential.

On the basis of sensitivity, the order of sensitivity was rainfall amount> moisture storage capacity>slope gradient. These model parameters are related to parameters that can trigger the transport capcity of runoff being the major limiting factor.

With respect to soil moisture modelling, despite the simplicity of the Thornthwaite and Mather model, it appears that the model can work quite satisfactorily in the study area. Annual runoff results were almost equal to estimated annual stream flow results from the study area. With respect to soil moisture it was impossible to independently verify the performance of the model, as this requires data on moisture content of the profile through out the year, which was not determined due to time constraints.

6. Conclusions and Recommendations

6.1. Conclusions

Two models were applied to estimate the rate of soil erosion in relation to the soil moisture in the Zacándaro sub-watershed. The study has shown different soil erosion rates with respect to landscape, individual mapping units and land use/cover. In general the greater part of the study area has soil erosion rates that are below the threshold values of 10 t ha^{-1} yr^{-1}, although in some parts with annual crops and perennial crops the erosion rates are above these threshold which calls for concern. The study has also shown there is a relationship between the predicted soil erosion rates and soil moisture in the study area. This entails that conversion from one land use type to another could significantly alter the hydrological balance resulting to soil losses.

Although the RMMF model has not been tested in volcanic soils, this study shows that it can be used in combination with Thornthwaite and Mather model as a tool for conservation planning. This is especially useful in identifying erosion prone areas in relation to soil hydrological conditions. The models are based on modest data requirements, a common limitation in developing countries. RMMF model parameters can be easily obtained from field survey or literature while those of the Thornthwaite and Mather model can easily be obtained from the standard meteorological centres.

With respect to GIS, this study has further demonstrated the usefulness of raster-based GIS as a tool in qualitative and quantitative assessment of soil erosion and soil moisture modelling. The use of GIS has provided a useful environment for parameterization, data compilation (collection), analysis and manipulation in a dynamic manner and within a short period.

The study has also shown that it is possible to use output of one model as an input of another model during the parameterization. Further, the study has proved that despite the lacking of quantitative data needed for validation, a combination of techniques can be used to provide an independent method to corroborate the performance of the model

6.2. Limitation of the study

Looking carefully at the soil and land use data, most values for input parameters were gathered from literature. Some parameters such as local rainfall interception of every crop, soil detachability, moisture content at field capacity, crop evapotranspiration coefficient, effective hydrological and rooting depth were readily not available necessitating it to be taken from the literature. Gathering this data takes time, but continuous research to obtain the actual values of these parameters for the local conditions would have provided a much better picture about the capability of the models especially in volcanic soils that behave differently from other mineral soils.

6.3. Recommendations

The evaluation of validity of the modelled soil predictions and soil moisture were based on qualitative criteria due to the absence of independent data from controlled erosion plots as well as components of water balance. With respect to the soil erosion modelling, there is a need for a quantitative data to validate the results of RMMF model using reliable results from runoff plots. These plots should cover all the representative landscape units as well the dominant land uses and cover types in the Zacándaro sub-watershed taking into consideration the spatial and temporal variability of these important variables. With respect to soil moisture modelling there is need to generate the necessary hydrological parameters for running and validation of the model. These parameters include the soil moisture storage capacity of the profile as well as the rooting depth. A real time data-recording scheme for stream flow should be established if possible. This will enable monitoring of stream variation throughout the year.

With respect to the accuracy of predicted soil erosion rates, there is a need to assess the errors associated with these predictions. This comes from the fact that the model predictions may be subjected to errors due to inaccuracies inherent in data and the limitation of the methods used to derive the component factor values. Processing of data input into the model required use of several algorithms, each of which may accentuate existing errors in data and propagate through the model resulting in uncertainty in the estimated rates.

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Appendices

Appendix 1: Laboratory analysis and field data results

Results of laboratory analyses

SMU	% Clay	% Silt 0.002-0.02 mm	% Silt 0.02-0.05 mm	% Sand 0.05-0.5 mm	%Sand 0.5-1mm	%Sand 1-2mm	Textural Class	%OM
Pi111	6.4	17.7	5.4	66.3	3.5	0.6	SL	7.0
Pi211	7.0	17.6	6.8	66.3	2.0	0.3	SL	24.1
Pi221	6.4	17.7	5.4	66.3	3.5	0.6	SL	7.0
Pi311	3.4	10.6	5.6	79.2	1.2	0	LS	3.2
Pi411	4.1	8.7	5.9	76.3	4.5	0.6	LS	6.7
Pi421	8.2	18.0	5.7	65.6	2.0	0.4	SL	9.2
Pi431	9.9	22.5	6.8	58.4	1.5	1.0	SL	12.0
Pi511	1.3	2.8	2.2	86.0	7.2	0.4	S	0.8
PM111	1.1	9.5	4.2	84.7	0.5	0	LS	0.9
PM211	1.1	9.5	4.2	84.7	0.5	0	LS	0.9
ZP111	7.3	21.5	6.8	60.6	2.4	1.4	SL	13.6
ZP211	5.9	19.3	8.6	62.5	2.6	1.1	SL	9.2
ZP311	7.5	17.6	8.1	64.2	1.9	0.8	SL	12.8
ZP321	7.5	17.6	8.1	64.2	1.9	0.8	SL	12.8
ZP411	9.8	18.7	5.0	57.5	4.3	4.7	SL	9.6
ZP421	15.9	19.5	8.4	53.2	1.6	1.3	SL	9.2
Labex 42	44.4	29.7	6.3	14.0	3.2	2.3	C	nd
Labex2	25.7	17.0	7.2	1.7	7.1	41.3	SCL	nd
Control OM	nd	nd	nd	nd	nd	nd	nd	99.3

Note: Labex 42 and Labex 2 quality control samples had 46 and 26 percent clay respectively, while Organic matter control sample had >99%.

Summary of simple field-tests results

SMU	No. of Observation.	Shear vane	Crumb Test	Manipulation Test	Water Acceptance Test	Pin hole Test
Pi111	3	3.4	1	6	7.8	4
Pi211	3	1.9	1	6	63.1	2
Pi221	3	3.4	1	6	7.8	4
Pi231	3	1.2	2	6	8.0	4
Pi311	3	2.8	2	6	41.2	4
Pi411	3	3.3	2	6	9.5	4
Pi431	3	1.8	2	6	10.5	4
Pi511	3	1.4	2	6	18.2	4
PM111	3	2.7	2	6	6.6	4
PM211	3	2.7	2	6	6.6	4
ZP111	3	3.2	2	3	20.5	2
ZP211	3	3.5	1	6	5.4	4
ZP311	3	1.8	1	6	18.5	3
ZP321	3	1.8	1	6	18.5	3
ZP411	3	2.5	2	6	22.4	3
ZP421	3	2.9	1	5	27.3	3

Semi quantitative soil erosion assessment results

Location		**Replicate 1**							**Replicate 2**							**Replicate 3**						
X	**Y**	a1	a2	a3	a4	b	c	d	a1	a2	a3	a4	b	c	d	a1	a2	a3	a4	b	c	d
790580	2150442	0	2	0	1	0	0	0	0	3	0	2	0	0	0	0	3	0	2	0	0	0
790490	2150275	3	3	2	1	1	1	2	2	2	3	1	0	2	2	4	3	3	1	0	2	2
790439	2149354	1	2	1	2	0	0	0	2	2	1	2	0	0	0	2	0	1	2	0	0	0
789228	2149209	3	0	1	1	0	0	0	2	0	2	2	0	0	0	2	0	1	2	0	0	0
789292	2149173	4	1	2	1	1	1	0	4	1	2	1	1	2	0	4	1	2	1	1	3	0
790458	2149151	4	1	1	2	2	2	0	3	0	2	2	1	1	0	4	1	2	2	2	1	0
790458	2149151	1	0	1	2	0	0	0	1	1	0	2	0	0	0	1	0	0	2	0	0	0

Appendix 2: Attribute table for AWHC

Land use/Land cover	Texture	Available Water Holding Capacity at Root Depth
Closed Forest	Loamy Sand	250
Closed Forest	Sandy Loam	300
Closed Forest	Sand_Sandloam_Loamysand	297
Closed Forest	Sandyloam_Clay	385
Closed Forest	Loamy sand_Sandylom	290
Open Forest	Loamy sand	250
Open Forest	Sandy loam	300
Open Forest	Sand_Sand loam Loamy sand	297
Open Forest	Sandy loam_Clay	385
Shrubs	Loamy sand	100
Shrubs	Sandy loam	150
Shrubs	Sandy loam_Clay	235
Grass Land	Loamy sand	100
Grass Land	Sandy loam	150
Grass Land	Sand_Sand loam_Loamy sand	147
Perennial Crops	Loamy sand	150
Perennial Crops	Sandy loam	250
Perennial Crops	Sand_Sand loam_Loamysand	247
Perennial Crops	Sandy loam_Clay	235
Annual Crops	Loamy sand	75
Annual Crops	Sandy loam	150
Annual Crops	Sandy loam_Clay	185
Annual Crops	Loamy sand_Sandyloam	140
Bare Soil	Loamy sand	100

Appendix 3: Equations used to generate monthly rainfall and temperature

Rainfall

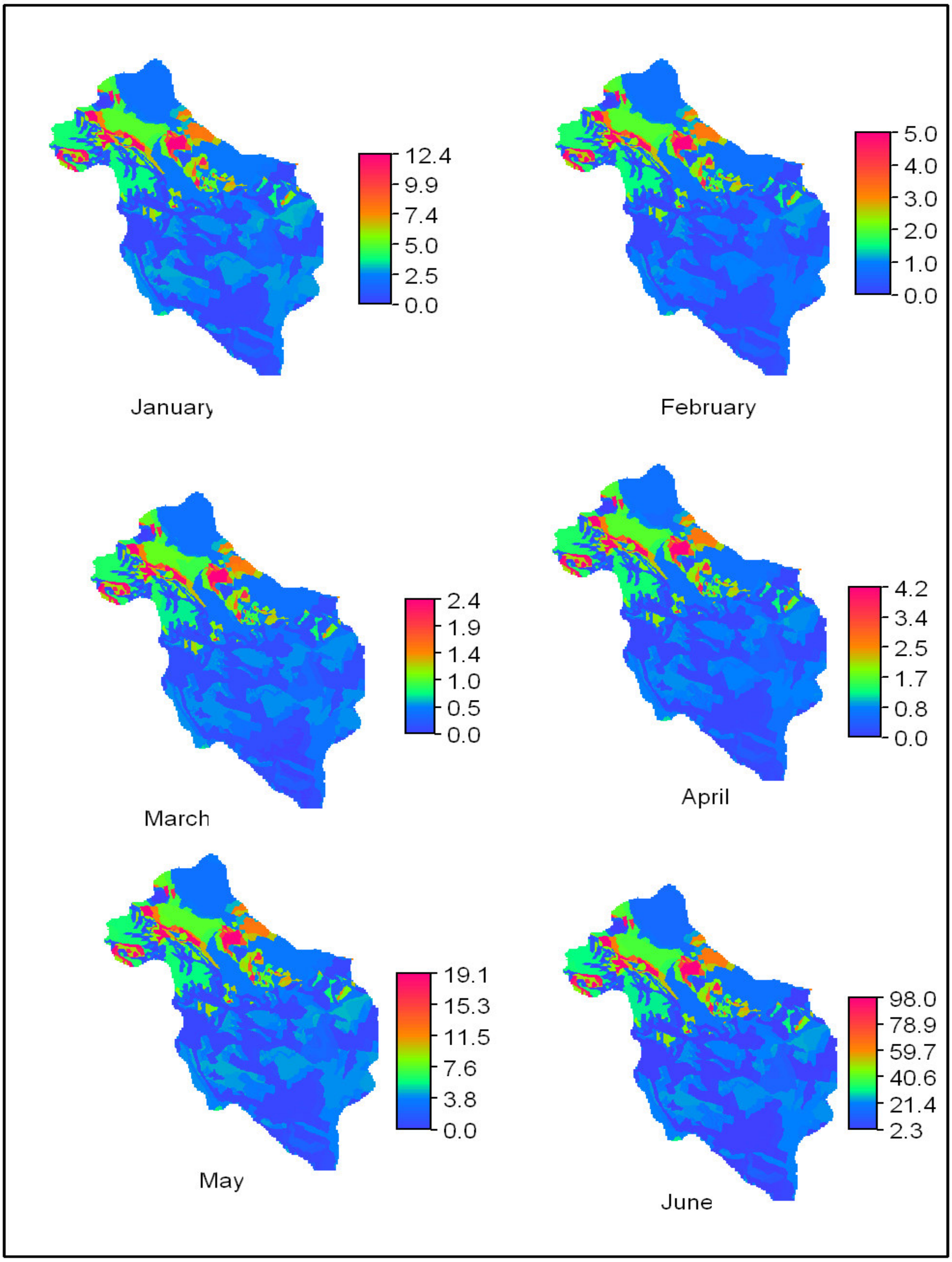
Month	Equation	Coefficient of Determination (R^2)	Correlation Coefficient (R)
January	Y = 0.0097x + 12.337	0.3609	0.6008
February	Y = 0.00059x- 0.3423	0.3609	0.6290
March	Y =0.00059x +0.2389	0.3949	0.6284
April	Y = 0.0048x + 0.1287	0.2645	0.5143
May	Y = 0.0154x + 17.897	0.5745	0.7579
June	Y = 0.0667x + 124.78	0.5961	0.7721
July	Y = 0.1107x + 129.53	0.6392	0.7995
August	Y = 0.0918x + 119.25	0.5367	0.7326
September	Y= 0.0823x + 130.79	0.5351	0.7315
October	Y = 0.0426x + 48.202	0.6201	0.7875
November	Y = 0.0119x + 16.532	0.5759	0.7589
December	Y = 0.0069x + 0.3411	0.6879	0.8294

Temperature

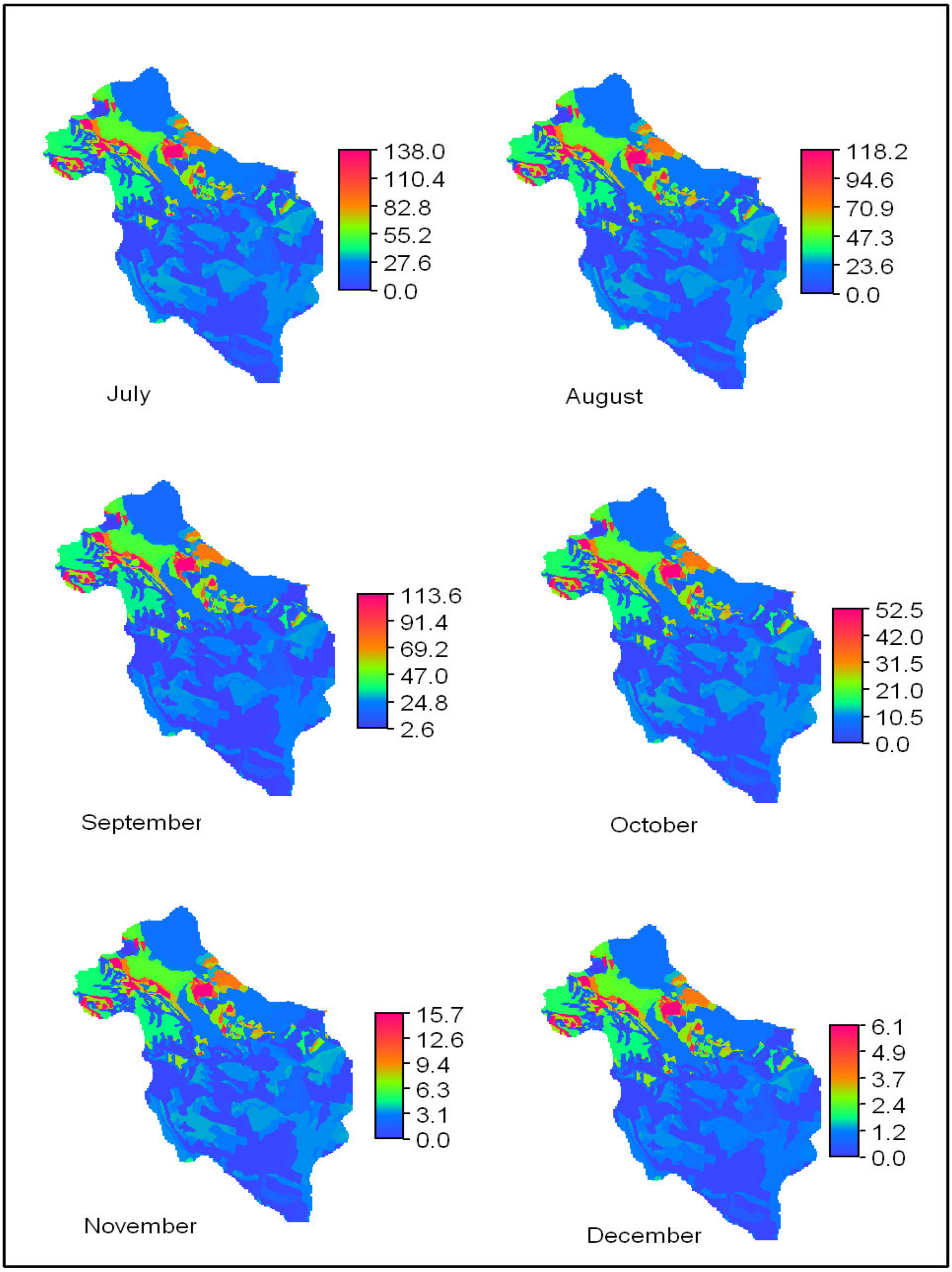
Month	Equation	Coefficient of Determination (R^2)	Correlation Coefficient (R)
January	Y = -0.0063x + 26.704	0.9702	-0.985
February	Y = -0.0073x+ 28.605	0.9742	-0.987
March	Y =-0.0072x + 30.091	0.9663	-0.983
April	Y =-0.0072x + 31.803	0.9604	-0.980
May	Y =-0.0057x + 31.445	0.9370	-0.968
June	Y = -0.0044x + 29.422	0.8724	-0.934
July	Y =-0.0035x + 27.068	0.8190	-0.905
August	Y =-0.0035x + 26.977	0.8154	-0.903
September	Y=-0.0039x + 27.158	0.8817	-0.939
October	Y = -0.005x + 28.233	0.9506	-0.975
November	Y =-0.0063x + 28.326	0.9761	-0.988
December	Y = -0.0064x + 27.61	0.9742	-0.987

Appendix 4: Soil moisture modelling monthly outputs

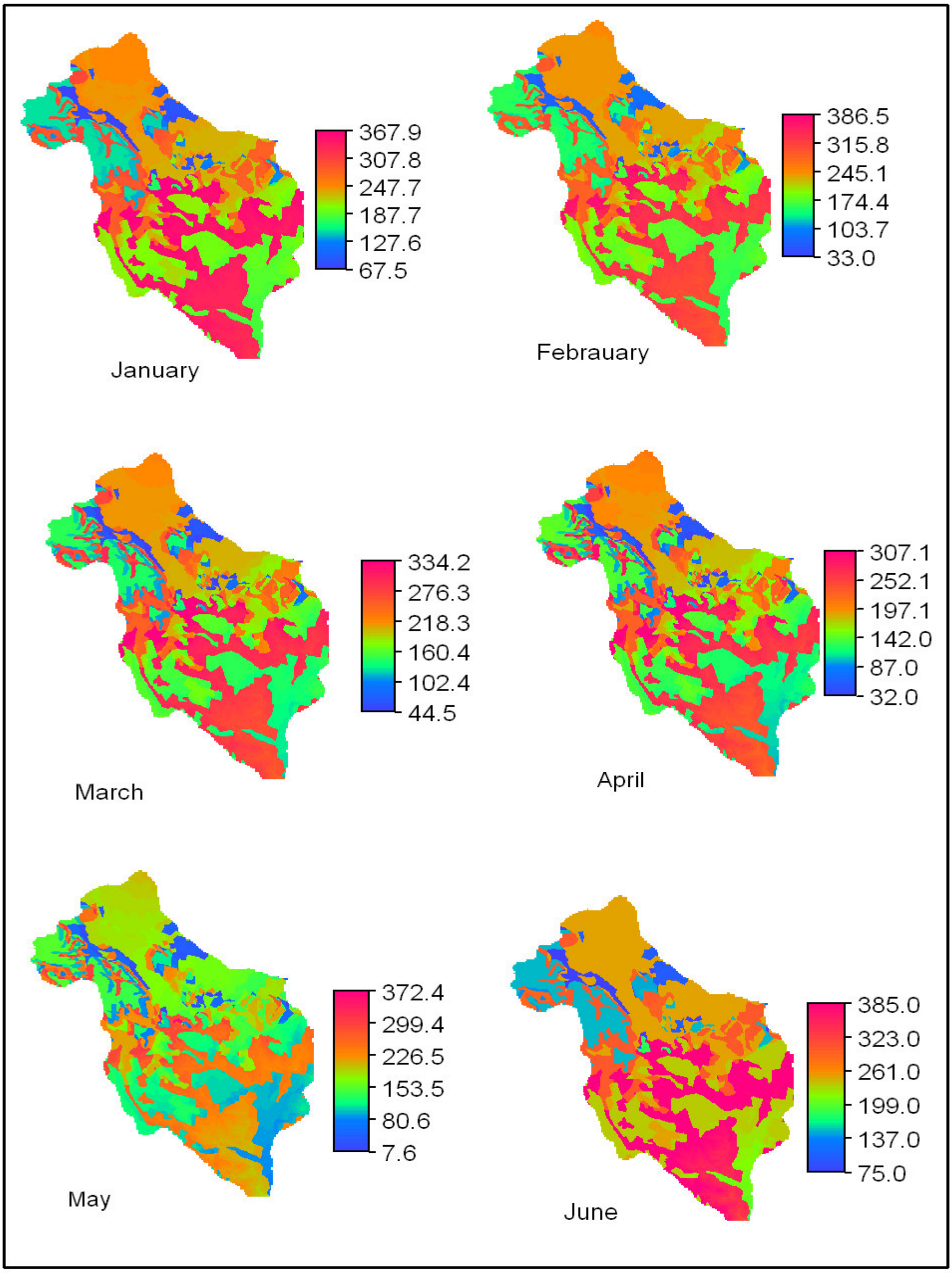
Monthly runoff



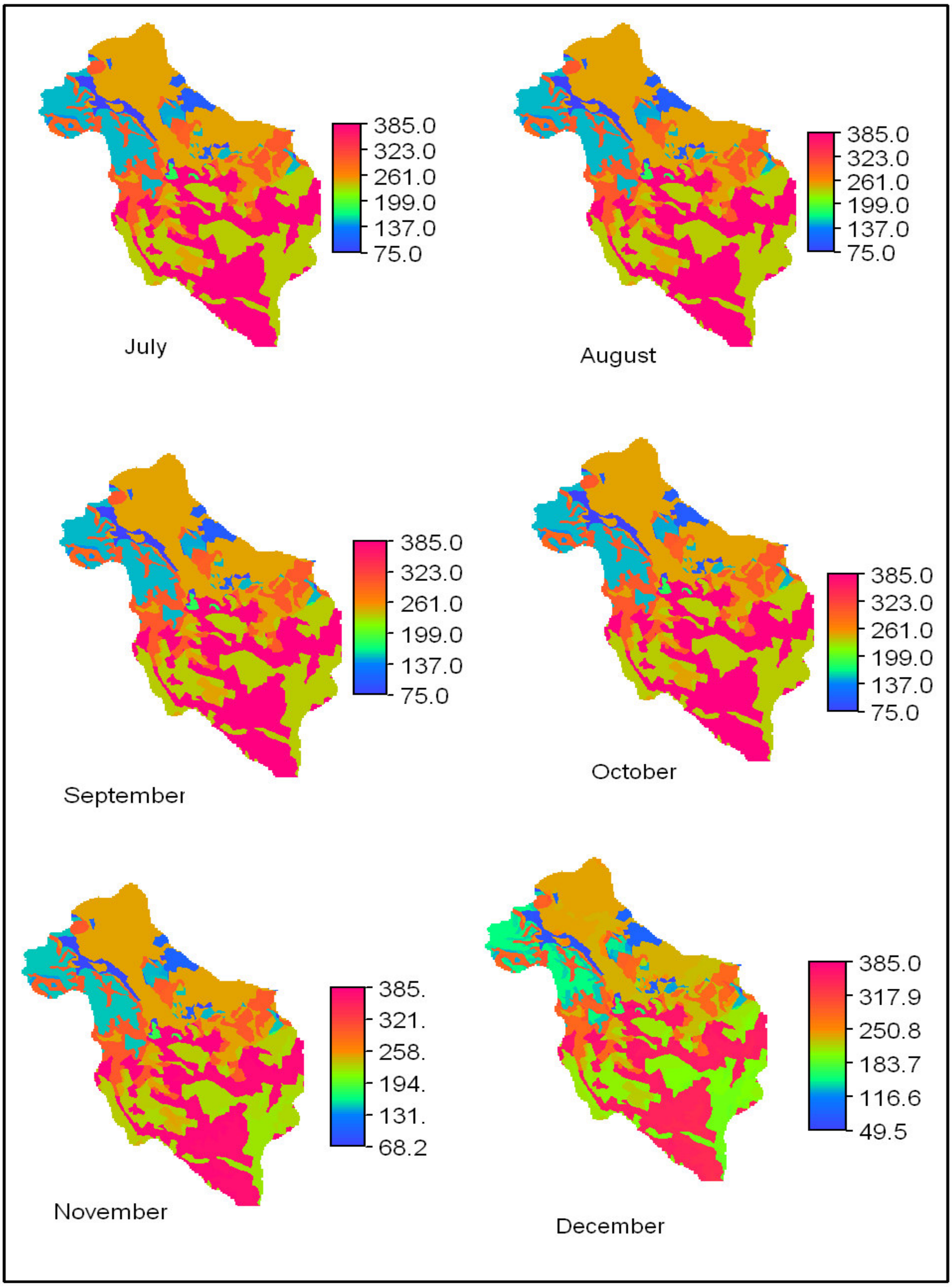
Monthly runoff continues



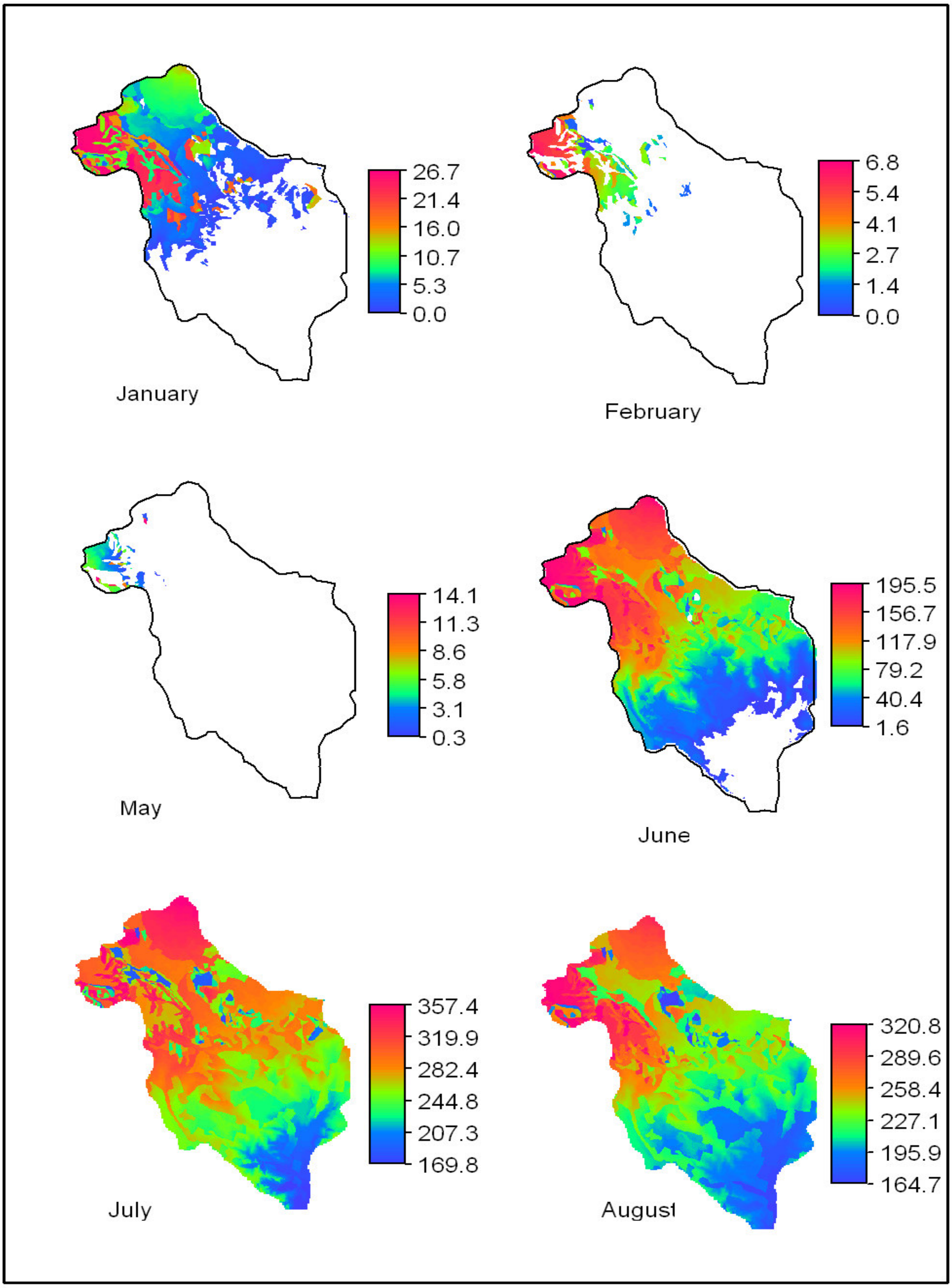
Monthly soil moisture



Monthly soil moisture continues



Monthly excess soil moisture



Monthly excess soil moisture continues