Ecology and Development Series No. 30, 2005

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Reservoir siltation in Ethiopia: Causes, source areas, and management options

Cuvillier Verlag Göttingen

To my late father **Tamene Desta** to whom I owe a lot and who would have been the most delighted person had he seen this stage of my work

ABSTRACT

A massive surface water harvesting effort is being undertaken in the drylands of Ethiopia aimed to improve the livelihoods of one of the most vulnerable people on earth, who are suffering from a combination of natural and human-induced environmental problems. However, most of the water harvesting schemes are under serious threat due to siltation. This could have profound socio-economic implications not only because of the financial loss for dam construction but also because the provision of additional water is the key alternative to improve the food security of people. There is therefore an urgent need to undertake relevant management interventions to reduce the accelerated loss of the water storage capacity of the reservoirs. An appropriate management plan requires information on how severe the problem is, what the determinant factors are, which landscape positions are the most vulnerable, and which management practices are more effective to tackle the problem in an efficient and cost-effective manner. This study is the first attempt in the country conducted with the aim of achieving the above goals at the catchment scale. Reservoir surveys were conducted to estimate the magnitude and rate of sediment yield of representative catchments in the highlands of northern Ethiopia. Corresponding catchment environmental variables were collected and correlated with the sediment yield data to assess the major determining factors of sediment yield variability. Terrain-based distributed models were used in a GIS to identify the major "hot-spot" areas of erosion to aid the implementation of efficient conservation practices targeted at the major problem areas. In addition, different land-use and land-cover (LUC)-redesign-based spatial scenarios were simulated to evaluate the contribution of reorganizing protective covers across sensitive landscapes in reducing on-site erosion and its potential delivery. The results of the study show that the annual siltation rate of the reservoirs ranges from 3 to 49 t ha^{-1} y^{-1} with an average annual rate of about 19 t ha^{-1} y^{-1} which is higher than the global and African averages of 15 and 10 t ha^{-1} y^{-1}, respectively. With these high annual rates of siltation, most of the reservoirs have lost more than 100% of their dead storage capacities within less than 25% of their anticipated design life. Statistical analyses of the relationship between sediment yield in reservoirs and environmental attributes of the catchments show that gullies, height difference, LUC-types, and surface lithology play significant roles in determining sediment yield variability between catchments. The soil erosion models depicted the spatial pattern of erosion and helped to identify landscape positions that are critical sources of sediment. The LUC-redesign-based spatial scenarios applied in a GIS demonstrate that reorganizing LUC-types so that protective dense covers are spread across the hot-spot areas of erosion enables the reduction of soil loss by about 65% compared to the existing condition. The study demonstrates that appropriate site selection, catchment rehabilitation, and protection before and after dam construction, would be necessary if the water harvesting schemes are to provide their intended services. As siltation is only one of the major problems, integrated assessment of all issues that threaten the potential benefit of the water harvesting schemes is needed.

Stauseesedimentierung in Äthiopien: Gründe, Sedimentquellen und mögliche Managementmaßnahmen

KURZFASSUNG

In den Trockengebieten Äthiopiens wird im Rahmen eines groß angelegten Wasserbewirtschaftungsvorhabens versucht, durch den Bau von Staudämmen und die damit verbundene Speicherung von Oberflächenwasser, die Lebensumstände der Bevölkerung, die unter natürlichen bzw. von Menschen verursachten Umweltprobleme leidet und zu den ärmsten der Welt gehört, zu verbessern. Die Speicherleistungen der meisten Staudämme werden jedoch ernsthaft durch Sedimentierung bedroht. Die Folgen sind von tief greifender sozioökonomischer Bedeutung, nicht nur wegen der Investitionsverluste, sondern auch weil ein zusätzliches Wasserangebot entscheidend zur Nahrungssicherheit der Bevölkerung beiträgt. Entsprechende Management-maßnahmen sind daher dringend notwendig, um den fortschreitenden Verlust der Speicherfähigkeit der Stauseen aufzuhalten. Um das Problem effizient und kosteneffektiv zu lösen, müssen die Fragen „wie ernst ist das Problem?“, „welche Faktoren führen zur Sedimentierung?“, „welche Positionen in der Landschaft sind am meisten gefährdet“ bzw. „welche Art des Managements ist am effektivsten?“ beantwortet werden. Diese Studie ist die erste in Äthiopien, die auf der Ebene des Wassereinzugsgebietes versucht, diese Fragen zu beantworten. Um Ausmaß und Geschwindigkeit der Sedimentierung in repräsentativen Einzugsgebieten im Hochland im Norden Äthiopiens zu bestimmen, wurden ausgewählte Stauseen untersucht. Die entsprechenden Umweltvariablen der Einzugsgebiete wurden erfasst und mit den Sedimentierungsdaten korreliert, um die wichtigsten Einflussfaktoren hinsichtlich Sedimentierungsvariabilität zu bestimmen. Geländegestützte verteilte Modelle wurden in einem GIS eingesetzt, um die wichtigsten hot-spot Bereiche zu bestimmen als Entscheidungsgrundlage für entsprechende Erosionsschutzmaßnahmen. Außerdem wurden räumliche Szenarien auf der Grundlage von Maßnahmen zur Umwandlung von Landnutzung bzw. Landbedeckung (LUC) simuliert, um den Beitrag von verbesserter Vegetationsbedeckung in empfindlichen Landschaftsbereichen bei der Reduzierung von Bodenerosion und der damit verbundenen Sedimentierung der Stauseen zu ermitteln. Die Ergebnisse zeigen, dass die jährliche Sedimentierung der Stauseen 3 bis 49 t ha^{-1} $Jahr^{-1}$ (durchschnittlich ca. 19 t ha^{-1} $Jahr^{-1}$) beträgt. Diese Werte sind höher als der globale bzw. afrikanische Durchschnitt von 15 bzw. 10 t ha^{-1} $Jahr^{-1}$. Durch diese hohen Sedimentierungsraten haben die meisten Stauseen mehr als 100% ihres Stauvolumens innerhalb von weniger als 25% ihrer geplanten Lebensdauer verloren. Die statistischen Analysen der Zusammenhänge zwischen Sedimentierung in den Stauseen und den Umwelteigenschaften der Einzugsgebiete zeigen, dass Rinnen, Höhenunterschiede, Art von LUC sowie Oberflächenlithologie eine signifikante Rolle bei der Bestimmung der unterschiedlichen Sedimentierungsraten der verschiedenen Einzugsgebiete spielen. Die Modelle stellten das räumliche Erosionsmuster dar und erlaubten die Identifizierung der kritischen Quellen der Sedimentbildung in der Landschaft. Die räumlichen Szenarien zeigen, dass entsprechende LUC-Maßnahmen mit verbesserter Landbedeckung in empfindlichen Landschaftsbereichen die Bodenverluste durch Erosion um mehr als 65 % verringern können. Die Studie zeigt, dass eine sinnvolle Standortwahl und entsprechende Erosionsschutzmaßnahmen vor bzw. nach der Errichtung der Staudämme zur erfolgreichen Wasserspeicherung notwendig sind. Da die Sedimentierung nur eines der Probleme darstellt, ist eine integrierte Bewertungen aller Faktoren, die den potentiellen Nutzen dieser Art der Wasserbewirtschaftung in Frage stellen, erforderlich.

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1 INTRODUCTION

1.1 General

The people of Ethiopia are amongst the most vulnerable in the world. Food insecurity is a serious problem in the country, especially in the arid and semi-arid areas. Analysis of the rainfall data since the 1950s indicates that draughts/famines have occurred in most parts of the country almost every 2 years (NMSA, 1996a, b). The increasing frequencies and intensities of draughts/famines in the country are mainly caused by declining rainfall and its unreliability (EPA, 1998). The increasing decline and unreliability of rainfall and the associated droughts/famines have pledged many human and livestock lives in the country (Hurni, 1993; EPA, 1998). The effects of unreliable rainfall and repeated droughts on the livelihoods of farmers are more serious because they have limited options to cope with such disasters.

In addition to the critical demand to sustain the productivity of rainfed agriculture, which supports more than 85% of the population, the rapid population growth in the towns and rural areas and the recent expansions in small- and medium-scale industrial enterprises have increased the demand for water. Under such circumstances, the existing water supply is inadequate to meet the increasing demand. Additional water supply and its proper utilization are therefore essential to improve food security and satisfy the growing needs. Effective exploitation of the existing surface water potential of more than 123 billion m^3 (Seyoume, 2002), of which only 5% is used for irrigation purposes (Gebeyehu, 2002), could be an alternative approach to improve the food security situation in the drought-prone semi-arid areas.

Against this background, the government of Ethiopia, in collaboration with the United Nations Economic Commission for Africa (UNECA), the United Nations Development Program (UNDP) and the Food and Agriculture Organization of the United Nations (FAO), launched the “Sustainable Agriculture and Environmental Rehabilitation, Reconstruction and Development Program (SAERP)”, with the main objective of increasing food production using water harvesting schemes for irrigation. To this effect, appropriate institutional arrangements were made in the different regions and intensive construction of micro-dams started in 1995.

The Tigray administrative region, where water scarcity is one of the most severe problems in the country, was one of the prime focal point of the water harvesting schemes. In this region, an institution called Commission for Sustainable Agriculture and Environmental Rehabilitation in Tigray (CoSAERT) was setup to undertake the construction of micro-dams. Since 1995, over 50 micro-dams have been built in the region and a good deal was achieved in economic, hydrologic and ecological terms. In the areas where the schemes are in place, farmers are able to produce more than three- to seven-fold of their former yields (Teshalle, 2001; Behailu, 2002) and are cropping at least twice a year. This added a positive externality to the nearby urban areas, where fruits and vegetables have become more available and at low prices. The micro-dams also provide people with drinking water for themselves and their livestock without traveling long distances. The newly built micro-dams also result in the development of new springs due to increased ground water recharge (Woldearegay, 2001).

However, the sustainability of the aforementioned benefits is challenged by the failure of most of the reservoirs within a very short period of their planned life span. On top of the engineering related failures, seepage and siltation are the most important problems facing the reservoirs. Due to siltation, some of the water harvesting schemes have lost more than 50% of their storage capacity within less than 10% of their expected service time (e.g., Gebre-Hawariat and Haile, 1999). Such rapid failure results in the loss of the envisaged benefits of the reservoirs. Furthermore, it results in the loss of the opportunity cost of huge investments spent on the construction of the schemes[1].

Both natural and human-induced processes are responsible for high erosion that causes rapid siltation of reservoirs in the region. The topography is rugged with pronounced terrain that provides high energy of water flow. Protective surface cover is low and the soil materials are largely loose, which can easily be washed away. Rainfall is intensive and onsets after long dry season striking virtually an open soil with minimum surface protection. These attributes, combined with the prominent gullies, resulted in one of the most severe land degradation and soil erosion problems in the world (Eweg and Van Lammeren, 1996).

Since 2001, the government has abandoned dam construction in favor of small ponds partly due to the failure of the micro-dams and based on the premise that 'ponds are cost-effective to construct and easy to manage'. However, it has already been observed that the ponds are experiencing high siltation problems within just one year of

[1] CoSAERT (unpublished reports) estimated that, on average, construction of one dam could cost over Euro 182,000, which is about 2 million Ethiopian Birr (1 Euro is about 11 Birr in early 2005).

construction (Rämi, 2003). This means that the siltation problem is scale independent, and that efficient use of the water harvesting schemes requires tackling the problem of siltation first. The fact that the ponds are facing similar siltation problems within just one year of service is due to the lack of information on the controlling factors and possible conservation measures. The factors that have contributed to the failure of the dams are not well known, which otherwise would have been a good lesson for the successful implementation of yet another ambitious plan of water harvesting using ponds. There is, therefore, a need for a detailed study on the causes of siltation and the possible amelioration measures to ensure that the water harvesting schemes are able to provide their intended services.

Few plot-based studies were conducted to assess the severity of erosion in the country (e.g., SCRP, 2000). These studies are, however, too few to represent the heterogeneous environments of the country (Bewket and Sterk, 2003). Such plot-based studies cannot also be extrapolated to a catchment scale directly. Furthermore, some of the suspended sediment samplings at gauging stations were conducted at large basin scale with limited potential to be adapted for small catchment scale studies. There is, therefore, a need to estimate sediment yield of small to medium catchment scales (1 – 50 km^2) that can help improve the missing link between small plot- and large basin-based studies (e.g., Verstraeten and Poesen, 2001a). Studies at these scales are also important because many of the solutions to environmental problems such as soil erosion and non-point source pollution will require changes in management at the scale of these landscapes (Wilson et al., 2000). In addition, none of the studies that estimated sediment yields at the basin outlets attempted to correlate the results with environmental attributes to assess cause-effect relationships and identify major sediment source areas for targeted management interventions.

Considering the fact that water is the most crucial resource for the subsistence farmers and that, if the water harvesting schemes are to be successful, it is important to understand the major causative factors of siltation. Preventing the rapid siltation of reservoirs requires understanding of the causes and processes responsible so that cause-treatment-based corrective and preventive measures can be undertaken. In addition, since all positions of catchments do not experience equal level of erosion and serve as sources of sediment, identification of “hot-spot” areas is necessary for targeted site-specific management intervention. This study applies an integrated approach to investigate the major geomorphologic and anthropogenic factors controlling reservoir siltation, assess the spatial pattern of sediment source areas, and devise site-specific management interventions at a catchment scale. The results of the study could be useful to designing efficient land management plans aimed to reducing catchment erosion and reservoir siltation. The study could also help bridge the gap in the lack of adequate information between processes at the plot- and large basin- level. The approaches and results of the study, being conducted in a dryland region, could also contribute to other tropical arid- and semi-arid environments where water scarcity, the necessity of surface water harvesting and the associated siltation problem will remain crucial.

1.2 Main objectives

The major objectives of the study are:

- To determine sediment yield of catchments based on reservoir surveys;
- To understand the major catchment characteristics and anthropogenic practices that control sediment yield variability;
- To identify the position of the landscape where most of the sediment comes from using distributed models integrated in a GIS;
- To evaluate the effectiveness of different LUC-redesign and conservation measures to reduce rates of soil erosion-siltation.

1.3 Organization of the thesis

The thesis is organized into eight chapters. Chapter 1 introduces the problem and major objectives. Chapter 2 reviews the state-of-the-art: water harvesting and erosion- siltation processes. Chapter 3 describes the study area and general methodology. Chapter 4 discusses the methods and results of the reservoir surveys used to estimate sediment yield. Chapter 5 examines the determinant factors of sediment yield variability. Chapter 6 identifies major sediment sources areas using distributed erosion/deposition models. Chapter 7 simulates the potentials of LUC-redesign scenarios in reducing sediment yields of catchments. Chapter 8 summarizes the findings of the research, assesses its policy implications and highlights future areas of investigation.

2 THE STATE OF THE ART

2.1 Water harvesting as a means to improve food security

Food security, mainly in arid environments, is directly linked to availability of water. Decreasing rainfall with increasing variability and associated trends of water scarcity have been observed in Africa during the last 30 years (Hulme, 1992; Zeng et al., 1999; 2001). During this period, the continent has experienced repeated drought and famine affecting numerous people and their livestock (e.g., World Food Summit, 1996). The influence of drought on the natural resource base and food security is severe in poor countries where populations have few options to cope and avoid activities that may further accelerate land degradation. Such interlinked feedback loop between process of land degradation and increased poverty referred to as the “downhill spiral of unsustainability” could ultimately lead to the “poverty trap” (Greenland et al., 1994).

Rainfall variability is one of the most pervasive and unalterable sources of uncertainty impinging on agriculture in African nations (Ellis, 1996). Since the risk to agriculture is often related to water scarcity arising from the innate variability of rainfall patterns, strategies to combating land degradation in dry areas must be based on the provision of water and its proper conservation (Katyal and Vlek, 2000). Minimizing the deleterious impact of rainfall variability through adequate provision of water and its proper utilization could increase the coping capacity of people against shocks produced by rainfall variations and droughts, and improve food security. Water harvesting could help to irrigate crops, and water livestock, and could serve as an insurance against the failure of the rains in subsequent years (Lawrence et al., 2004).

Large areas of Africa have the potential to be highly productive, and yields can be substantially raised from present levels with appropriate land use and effective management of water resources. It is estimated that some 4, 200 billion m^3 of fresh water flows out of Africa into the ocean every year, and utilizing 10% of it would increase Africa’s food production by 10% (Nana-Sinkam, 1995).

Water harvesting schemes in Africa have been implemented for a long time, probably for about 9000 years (Nasr, 1999; WCD, 2000). However, awareness of the role of water harvesting in improving crop production grew in the 1970s and 1980s, when widespread droughts threatened agricultural production (Nasr, 1999). At present, several countries in the dryland areas are utilizing water harvesting techniques to collect and store rainwater for irrigation, power supply and human and livestock drinking needs. Ethiopia is one of the countries in tropical Africa striving to improve the food security of people through water harvesting schemes for small-scale irrigation.

The highlands of Ethiopia receive a high amount of rainfall. They are sources of several big rivers such as the Blue Nile, and the country has been called the "Water Tower of East Africa". However, "shortage of water" is the most serious problem facing the country, and Ethiopia is one of the most drought-stricken regions in the world, mainly due to highly erratic and unpredictable rainfall (EPA, 1998).

Compilation and analysis of the historical data acquired from various sources[2] indicate a generally increasing occurrence of drought/famine in Ethiopia (NMSA, 1996a, 1996b; EPA, 1998). During the period between 253 B.C and the 1st century A.D, one drought/famine was recorded every seven years. From the beginning of A.D to 1500 A.D, 177 droughts/famines were reported in the country, i.e., an average of one drought/famine every nine years. From the 16th century to the first half of the 20th century, the number (frequency) of droughts/famines recorded increased, with an average occurrence of one drought every seven years. From the 1950s onwards, 18 droughts/famines were recorded in 38 years, showing the occurrence of drought every two years. Analyses by NMSA (1987) and EPA (1998) also show that the highest frequency of droughts/famines occurred in the 2nd century A.D followed by the first part of the 20th century while on a decadal basis, 1970-1979 was the worst period, having seven disastrous drought/famine years. Generally, the worst period appears to be the decade beginning in 1980 and the worst drought year 1984.

Virtually all agricultural crop production in Ethiopia depends on rainfall that is frequently erratic and unpredictable (Conway, 2000; USAID, 2003). Under such conditions, surface water harvesting can be an alternative to supplement the rainfed agriculture with irrigation, which could help to increase the potential for producing more food more consistently in the drought-prone food-insecure areas (CoSAERT 1994; Waterbury and Whittngton 1998; Catterson et al., 1999). According to FAO's (1986) estimation, exploitation of the potential irrigation in the country could increase agricultural production by 40%.

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[2] Sources of data are various documents available nationally and internationally including unpublished material, which is locally available in manuscript form (NMSA, 1996a; 1996b).

Supplementing rainfed agricultural crop production with traditional irrigation has been implemented in Ethiopia since the Pre-Axumite period (560 BC) (Fattovich, 1990; Catterson et al., 1999; Seyoum, 2002). In spite of its long history, however, only 5% of the potential 4 million ha is under irrigation (Gebeyehu, 2002). Currently, the rapid population growth in both urban and rural areas, the expansion of small- and medium-size industrial enterprises, and above all the increasing frequency of drought and famine due to rainfall shortage and/or variability, have significantly increased the demand for water. As a result, the government of Ethiopia launched a big project on water harvesting schemes in 1995. The main objective was to increase self-sufficiency in food production using water harvesting systems for irrigation. The undertakings in the administrative region of Tigray, northern Ethiopia, are briefly discussed below. The major achievements of the water development strategies in the region and the problems faced are reviewed.

2.2 Water harvesting in Tigray: potentials and problems

According to CoSAERT (1994), the Tigray region has more than 9 billion m^3 of water as runoff, all of which disappears without being used. The possibility of using about 50% of this potential could irrigate half a million hectares of land, which could feed 3 times the present population of the region (CoSAERT, 1994). To exploit this potential, an ambitious plan of constructing about 500 dams in ten years was devised in 1995. The construction of the 500 dams was expected to irrigate 50,000 hectares, which would result in the production of 200,000 tons of grain equivalent, enough to feed an extra 930,000 people who otherwise would be dependent on food aid (CoSAERT, 1994). To date, around 50 dams have been built (Figure 2.1), which increased the areas of potentially irrigable land by about 2000 ha (Behailu, 2002).

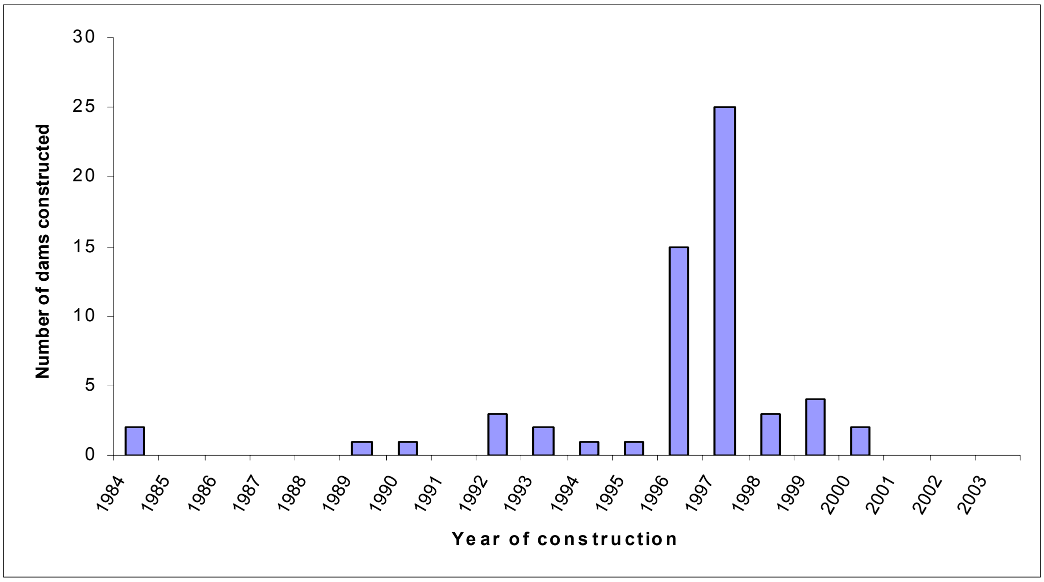


Figure 2.1: Number of micro-dams constructed in Tigray, N. Ethiopia by year. The dams' capacities range from 3.10 $*10^6$ m^3 to $0.11*10^6$ m^3 and a height of 9 to 24 meters. In an international context, the dams can be classified as small to medium size[3] (Source: CoSaERT unpublished reports)

The construction of the dams (though only 10% of the plan was achieved) resulted in various economic, hydrologic and ecologic benefits. A socio-economic impact assessment study conducted for some reservoirs indicated that farmers were able to increase yields 3- to 7- fold by using irrigation from the water harvesting schemes (Teshalle, 2001; Behailu, 2002). Our interviews with local farmers in six reservoir perimeters indicated that they managed to produce 2-3 times more cereals (e.g., maize). Farmers who did not previously produce any fruits and vegetables are now able to grow tomatoes, vegetables and different fruit crops, which has increased their income. Before the construction of the surface water harvesting schemes, people and livestock used to travel long distances (up to 15 km) to fetch drinking water. Since the construction of dams, people and livestock have been able to get enough water easily even during drought periods (Figure 2.2).

[3] According to the International Commission on large dams, dams are classified to be "large" if height is greater than 5 meters and volume of storage is more than $3*10^6$ m^3 or if height is bigger than 15 meter (WCD, 2000).

Figure 2.2: Water harvesting and its benefit to livestock. Livestock have access to drinking water even during drought seasons. Photos taken during the low rainfall season of April, 2002/2003

A study by Woldeageray (2001) shows that the ground water level has risen, and that wells that used to be dry throughout the year continued to carry water the whole year due to groundwater recharge after the construction of the dams. Farmers' interviews also indicated that most of the new springs that developed as a result of the newly built dams did not dry up even during drought seasons. An increase in ground water level due to groundwater recharge favors sustainable groundwater development such as water supply, irrigation and industries. Woldearegay (2000) also shows an improvement of the groundwater quality of localities in areas where water harvesting schemes were in place.

The development of new springs, recovery of older dry wells and springs, and an increase in groundwater level also improve the local soil moisture content. There is clear evidence in Tigray that areas behind dams are greener than areas upslope. In most places, livestock fodder is being harvested or used on the spot for restricted grazing even during drought seasons, and it is common to see shimmering green areas in contrast to the dry, barren surrounding hills (Catterson et al., 1999). After the construction of the water harvesting structures, the microclimate of the surrounding areas has also improved. The hot and dry air is replenished by moist and cool air, promoting life around the micro-dams. The water harvesting schemes have also attracted aquatic species, both plants and animals. They serve as the home of different birds, increasing the species diversity around that particular locality.

The reservoirs constructed in the region also contribute greatly to the reduction in soil losses and the off-site effects such as rapid siltation of downstream dams and rivers. A study conducted on four reservoirs, for instance, indicated an average annual deposition of over 125,000 tons of soil (Gebre-Hawariat and Haile, 1999). If this result is extrapolated to the existing 50 micro-dams in the region, over 500,000 tons of soil could be kept within the watersheds every year. This demonstrates the benefits of reservoirs with respect to reducing soil loss as well as sedimentation downslope.

Despite the various benefits obtained from the construction of the micro-dams, there are critical problems facing the schemes. Almost all reservoirs have one problem or another, the major ones being engineering failures, excessive seepage and rapid siltation. Due to the ambitious plan of constructing as large number of dams in the shortest time possible, adequate studies related to proper site selection and catchment management before dam construction were not conducted. Inadequate information regarding foundation and embankment stability, weak compaction of embankments, and lack of experience in geotechnical engineering related to the design of dam embankments contribute to seepage. On the other hand, the absence of catchment management and location of dams at the junctions of two or more collapsing gullies led to increased siltation. The rate of siltation is so high that some reservoirs lost over 50% of their storage capacity in less than 10% of their anticipated service time (Gebre-Hawariat and Haile, 1999). This results in the loss of the expenditures used to construct the dams, and failure to improve the food security of people using small-scale irrigation.

Despite the fact that erosion is the driving force of siltation, the magnitude of the process, major responsible factors, major source areas of sediment and the possibilities of ameliorating the problem have not been investigated. Such analyses are crucial, as water would remain to be the key element in the improvement of food security in the semi-arid areas of the country.

2.3 Soil erosion and its impacts

Soil is being degraded on an unprecedented scale, both in its rate and geographical extent (e.g., Valentin, 1998). The major cause of soil degradation is soil erosion (e.g., Oldeman, 1994; Morgan, 1995), which is also perhaps one of the most serious mechanisms of land degradation and soil fertility decline (e.g., El-Swaify, 1997; Enters, 1998). Generally, natural and human factors are responsible for continued erosion and land degradation. Climate change and irregularity of rainfall are the major natural factors. Population growth on limited agricultural land which requires bringing marginal and fragile lands under production as well as intensified use of the already stressed resources to satisfy the basic necessities of life, aggravates further erosion and decreasing productivity resulting in a population-poverty-land degradation nexus (Lal, 1990; Katyal and Vlek, 2000). The processes and impacts of soil erosion are more pronounced in tropical regions due to intensive rainfall, highly weathered erodible soils, poor vegetation cover and greater potential energy of water flow in steeper areas (e.g., Lo, 1990; Olofin, 1990; El-Swaify, 1997; Enters, 1998). The economic implication of soil erosion is more significant in developing countries because of lack of capacity to replace lost nutrients (Erenstein, 1999).

The on- and off-site effects of erosion result in the loss of soil and its nutrients from basins and in sedimentation of water bodies. The physical removal of top soil by erosion could result in a truncated A-horizon, in which crop production may no longer be productive. The loss of nutrient-rich top soil leads to loss of soil quality and hence reduced crop yield (Stoorvogel and Smaling, 1998). Severe erosion can lead to deep and wide gullies, which can hamper agricultural practices. Erosion could also result in flooding and property damage both on-site and off-site, including the destruction of infrastructure such as roads, hydro-electric supplies, deposition in irrigation canals, reservoirs, and in the flooding of settlements (Verstraeten and Poesen, 1999). Soil and nutrient loss to downstream sites could lead to sedimentation and pollution of water resources. Generally, the off-site impacts of soil erosion on water resources are more costly and severe than the on-site impacts on land resources (Phillips, 1989).

Soil erosion by water and its associated effects are recognized to be severe threats to the national economy of Ethiopia (Hurni, 1993; Sutcliffe, 1993). Since more than 85% of the country’s population depends on agriculture for living, physical soil and nutrient losses lead to food insecurity. Hurni (1990, 1993) estimates that soil loss due to erosion in Ethiopia amounts to 1493 million tons per year, of which about 42 tons ha^{-1} y^{-1} is estimated to have come from cultivated fields. This is far greater than the tolerable soil loss as well as the annual rate of soil formation in the country. According to an estimate by FAO (1986), some 50% of the highlands of Ethiopia are already ‘significantly eroded,’ and erosion causes a decline in land productivity at the rate of

2.2% per year. The study also predicted that by the year 2010, erosion could reduce per capita incomes of the highland population by 30%.

The highlands of Ethiopia in general and the Tigray region in particular experience severe soil erosion mainly due to steep terrain, poor surface cover, intensive cultivation of slopy areas and degradation of grazing lands due to population and livestock pressure. In Tigray, virtually all topsoil and in some places the subsoil have been removed from sloping lands leaving stones or bare rock on the surface (Tilahun et al., 2002). Even though it is assumed that some of the soil can be trapped downstream, the areas that benefit from the transported soils are relatively small compared to those from which it was detached (Sonneveld and Keyzer, 2003). The eventual delivery of sediment to streams is also high due to steep slopes and exposed terrain, reducing the possibility of soil redistribution to benefit downstream settlers.

The available estimates related to soil degradation in the region provide a picture of the magnitude of the problem. Hunting (1974) estimated the average rate of erosion in the central highlands of Tigray to be above 17 metric tons ha^{-1} y^{-1}. Studies in the 1980s report estimates of erosion rates of more than 80 tons ha^{-1} y^{-1} (Tekeste and Paul, 1989). A study by Hurni and Perich (1992) indicated that the Tigray region has lost 30-50% of its productive capacities compared to its original state some 500 years ago. Other studies in central Tigray highlands also showed soil loss rate of about 11 tons ha^{-1} y^{-1} (Nyssen, 1997) and 7 tons ha^{-1} y^{-1} (Nyssen, 2001). Machado et al. (1995, 1996b) report soil losses of about 21 t ha^{-1} y^{-1} and 19 t ha^{-1} y^{-1} based on data from an in-filled dam and rainfall simulation, respectively. Gebre-Hawariat and Haile (1999) estimated a sediment accumulation rate of 18 – 63 tons ha^{-1} y^{-1} while Aynekulu et al. (2000) estimated sediment accumulation of 17 – 40 tons ha^{-1} y^{-1} for similar small reservoirs in the region.

The estimated soil loss rates indicated above show diversity, and their accuracy could be limited. However, the severity of erosion and associated land degradation in general is clear from evidence in the field (Figure 2.3). The persistent deterioration of the quality of the cultivated land and associated crop yields reflected by degraded upslopes, the ever expanding gullies and associated fragmentation of farm fields, the sedimentation of some lakes and reservoirs and the frequent power-cuts and electric power interruptions throughout the country due to the reduced water storage of dams are some examples.

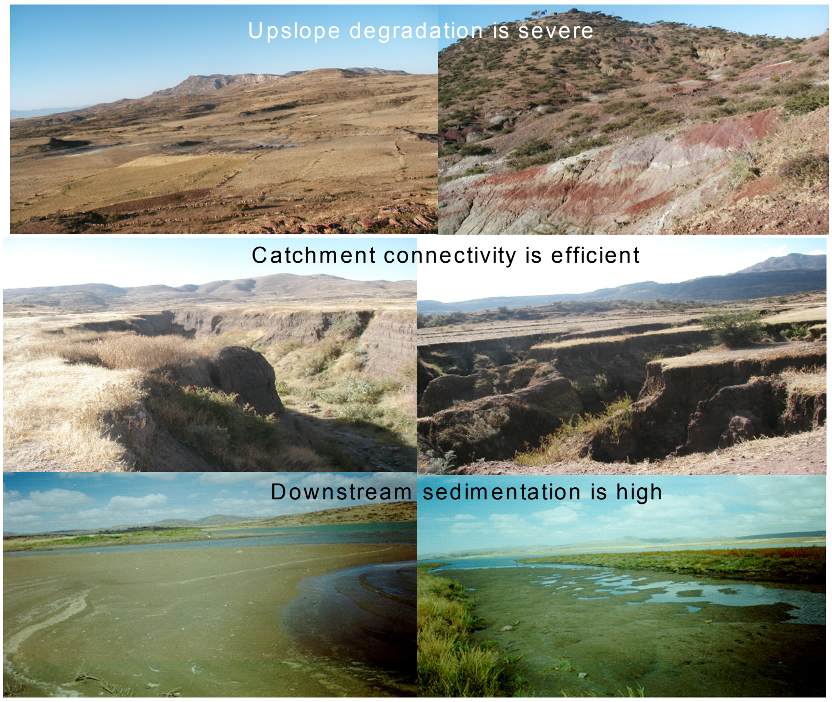


Figure 2.3: Severity of erosion and siltation in Tigray. Mountainous and slopy terrain, poor surface cover and steep slope cultivation, deep and wide gullies of high density are major characteristics of the region

2.4 Approaches to siltation assessment

Sediment yield estimation is crucial in water resources analysis, modelling and engineering, as sedimentation rates and amounts determine the performance and life of reservoirs (Lane et al., 1997). Understanding the causes and processes of siltation are prerequisites for management intervention necessary for reducing the off-site effects of accelerated erosion (Mitas and Mitasova, 1998a). Knowledge of cause-effect relationships and their spatial patterns are also essential for planning appropriate sites for future water harvesting schemes and for designing necessary management precautions (Verstraeten et al., 2003; Lawrence et al., 2004). A combination of bottom-sediment analysis and catchment monitoring provides a powerful conceptual and methodological framework for improved understanding of drainage basin sediment dynamics (Foster, 1995; Foster et al., 1990).

Different approaches are available for estimating reservoir siltation rates. The use of distributed physically based models, that determine catchment erosion and route the soil along channels to ultimately estimate sediment delivery, is becoming increasingly widespread (e.g., Ascough et al., 1997; Ferro et al., 1998; Van Rompaey et al., 2001). However, such models require extensive distributed data for calibration and validation, making their application difficult in data-scarce regions (Morgan, 1995; De Roo, 1998; Stefano et al., 1999).

Other approaches to estimating sediment yield are those based on sediment rating curves and river sampling (e.g., Dearing and Foster, 1993; Steegen et al., 2000). These methods require repeated measurements from representative samplings undertaken over frequent periods, which result in high operational costs (Verstraeten and Poesen, 2001b; 2002a). The main problem of such techniques is that measurements that are not based on continuous recordings could give unreliable estimates of sediment yields (Walling and Webb, 1981).

The bathymetric survey is another alternative used to estimate sediment yield. This approach is based on calculating the differences in the elevation of a reservoir-bed over a period of time during which original measurements were undertaken and the survey time (e.g., Rausch and Heinemann, 1984; Juracek and Mau, 2002). The main problem in the use of this method is “dislocation” or removal of original bench-marks, where the use of slightly different bench-mark locations could lead to huge errors (Butcher et al., 1992).

The use of sediment cores from reservoir deposits is another possibility for determining sediment yield (Duck and McManus, 1990; Butcher et al., 1993; Dearing and Foster, 1993; Schiffer et al., 2001; Verstraeten and Poesen, 2001a; Erskine et al., 2002). The major drawback associated with this method is that errors could be compounded, since several calculations and measurements are needed to derive sediment yield (Duck and McManus, 1990; Verstraeten and Poesen, 2001b; 2002a).

Among the aforementioned approaches, the reservoir sedimentation survey (bathymetry and pit-based) seems to be appropriate in terms of cost, speed and applicability. Verstraeten and Poesen (2000) highlight the role of dam sedimentation surveys to map sediment yield estimates and identify areas of high soil loss risk at low cost. Butcher et al. (1992) indicate that, in contrast to stream sampling or plot and pin measurement, reservoir survey is relatively simple requiring only a short field survey. Stott et al. (1988) argue that reservoir survey methods are more useful and representative, because measurements of sediment deposit do not involve generalized statistical models of sediment erosion and transport or spatial extrapolation of point and plot measurements. It is also shown that data derived from simple studies of reservoirs can provide a more reliable indication of sediment loss within the catchment than may be obtained from gauging stations and rating curves (Walling and Webb, 1981; Al-Jibburi and Mcmanus, 1993; Einsele and Hinderer, 1997). Considering the above issues, pit-based (dried-up reservoirs) and bathymetric (reservoirs filled with water) surveys were used in this study to estimate sediment deposition in reservoirs.

2.5 Approaches to soil erosion modelling

Sustainable land management and water resources development are threatened by soil erosion and sediment-related problems. In response to such threats, there is an urgent need to estimate soil loss and identify risky areas for improved catchment-based erosion control and sediment management strategies. Erosion models are considered to be the best options to predict erosion/deposition processes and identify major sediment source areas for targeted resource management applications (Lane et al., 1997).

Even though several models are available to predict soil erosion/deposition, there is no clear agreement in the scientific community on which kind of model is more appropriate for the simulation of natural processes (Bogena, 2001). Generally, two main types of model formulation[4], empirically and physically based, are available for predicting soil erosion (Foster, 1990). Most models in current use are of the hybrid type including both empirical and theoretical components (Haan et al., 1994).

Empirical models are based on extensive experimental results and input-output relationships. Such models have constraints of applicability to regions and ecological conditions others than from which data were used in their development (Merritt et

[4] Models can also be classified based on the way they model spatial variability (lumped versus distributed parameter models) and based on a temporal structure (single event versus continuous event models). Lumped models ignore spatial variability in order to simplify parameters inputs and computational requirements. Distributed models attempt to include the natural variability of parameter properties and processes. Single event models can provide real-time or near real-time prediction of natural events, while continuous models compute processes over longer time periods. Morgan and Quinton (2001) also distinguished between predictive models (used in practical applications such as to support land management decisions) and research models (primarily aimed at enhancing process understanding).

al., 2003). The site-specificity, parameter limitations, and problems of representativeness of empirical models require that considerable research be made to predict erosion before reliable use of the models can be made (El-Swaify, 1990; Stefano et al., 1999). Examples of empirical models include methods such as the Universal Soil Loss Equation (USLE) and its derivatives. The USLE is one of the most frequently used water erosion models. However, it has several limitations including its limited application to non-uniform slopes, its inability to explicitly represent hydrologic and erosion processes, and its inability to explicitly represent deposition and sedimentation processes, since the model does not differentiate those parts of the landscape experiencing net erosion and net deposition (Foster, 1990; Moore et al, 1991; Moore et al, 1992; Mitasova et al., 1997).

Physical process-based models are based on computation of erosion using mathematical representations of fundamental hydrologic and erosion processes incorporating soil detachment and transport (Foster, 1990). Such models may be applied across multiple landscapes and situations because the mathematical relationships are derived from physical laws, which must be obeyed under all circumstances (Maidment, 1996; Merritt et al., 2003). Some examples of process-based deterministic models include the Water Erosion Prediction Project (WEPP) and European Soil Erosion Model (EUROSEM). The major limitation of these models is that they are too complicated for initial assessment of erosion reconnaissance surveys and suffer from high computational costs (Mitasova et al., 1997, 1999; De Roo, 1998). These models also require high input with high spatial resolution in order to apply them to the full range of field conditions (Foster, 1990; Foster et al., 1995). The fact that a priori knowledge of the area prevails in the selection of parameters also introduces a strong degree of subjectivity in the calibration of process-based models (Favis-Mortlock, 1998), which means that the successful application of such models is dependent on the intervention of the user, rather than the model design itself (Botterweg, 1995).

Examples of models from the intermediate technology combining mathematical process descriptions with empirical relationships include Chemicals, Runoff and Erosion from Agricultural Management Systems (CREAMS), AGricultural Non-Point Source (AGNPS), Erosion Productivity Impact Calculator (EPIC), and Areal Nonpoint Source Watershed Environment Response Simulation (ANSWERS)

(Krysanova et al, 1998). These models have the inherent limitations of the empirical models and require relatively detailed data for calibration.

Recently, spatially distributed terrain-based models that emphasize the effect of terrain shape and topographic complexity on erosion/distribution processes have been in common use (Moore and Burch, 1986; Moore and Nieber, 1989; Moore et al., 1991; Desmet and Govers, 1996a; Mitasova et al. 1998; Van Oost et al., 2000). The central idea behind their theory is that topography is the dominant control over the spatial variation of hydrological processes and therefore topographic forms with additional basic soil and land cover related parameters can permit rapid estimation of spatial patterns over substantial areas and complex landscapes (Desmet and Govers, 1996a; De Roo, 1998, Wilson and Gallant, 2000).

Recent advances in the development of digital elevation models (DEMs) and GIS have promoted the application of distributed soil erosion and sediment delivery models at the catchment scale (Gurnell and Montgomery, 1998). GIS permits representation of the spatial heterogeneity of the catchment land use, soil properties and topography, which enables to provide spatially distributed predictions of soil erosion for complex three-dimensional terrain (Mitas and Mitasova, 1998a).

There exists considerable knowledge on the factors and processes that determine soil detachment, transport and deposition processes (Morris and Fan, 1998). However, as most knowledge has been developed for temperate croplands, less information is available for the tropics (Rose, 1997; Lal, 1999). Also, because prediction and control models developed in these investigations are predominantly empirical, they are not directly transferable to tropical settings (Harden, 1990). It is also difficult to reliably apply most of the models developed in the "data-rich" Western regions to developing countries, where both data availability and quality are critically poor. It is also important to recognize that there is no single model that can handle the complex processes of erosion/deposition and satisfy all our interests (Istanbulluoglu et al., 2002). Selection of appropriate model(s) that can suit the areas under study is therefore crucial.

Selection of models is generally determined by the objective at hand, resources available and detail and scale of investigation required. Considering the above issues, three terrain-based erosion models were applied in this study. The models are the

Stream Transport Capacity Index (Moore and Burch, 1986), the USLE2D (Desmet and Govers, 1996a) and the Unit Stream Power-based Erosion/Deposition (Mitasova et al., 1997, 1999). These models were selected considering their relatively minimum data demand for input and calibration as well as their suitability for complex terrain environments. Detailed descriptions of the three models are given in Chapter 6.

2.6 Spatial simulation for site-specific land management options

The effectiveness of land management decisions aimed at preventing the negative impacts of soil erosion in a complex landscape can be significantly improved by detailed predictions of erosion and deposition patterns for proposed land-use alternatives (Mitas and Mitasova, 1998a, b). Through simulating the impact of complex terrain, land use/cover (LUC) changes and soil properties on the spatial distribution of erosion/deposition, optimization of preventive measures aimed at creating a sustainable landscape is possible (Mitasova et al., 2001). There is also a strong belief that through landscape or ecological restructuring it will be possible to apply targeted conservation measures and land-use practices, which can protect the environment and improve productivity (Vlek, 2001). Pimentel et al. (1995) pointed out that the implementation of appropriate soil and water conservation practices has the potential to reduce erosion rates significantly.

A sound knowledge of spatial variations in sediment production and delivery is necessary when implementing soil conservation policies. A targeted response should be employed and resources directed to areas of high risk rather than spreading them equally across the landscape (Adinarayana et al., 1998; Boardman 1998). Identification of hot-spot areas of major sediment sources is, therefore, crucial to target resources to relevant locations. Once these areas are identified, different management and land use planning scenarios can be implemented to reduce soil loss and sediment yield. Reorganizing catchment LUC and management practices at locations of high soil loss risk could enable reducing the siltation rate of reservoirs. The main aim of Chapter 7 was to test the sediment yield reduction potentials of different simulation scenarios, mainly alternative LUC redesign options in some selected sites.

3 STUDY AREA AND METHODOLOGY

3.1 Study area

This study was conduced in the highlands of northern Ethiopia, Tigray. The region lies within the zone of sub-Saharan Africa, located in the horn of Africa (Figure 3.1). Brief descriptions of the environmental conditions of Ethiopia and Tigray are given below.

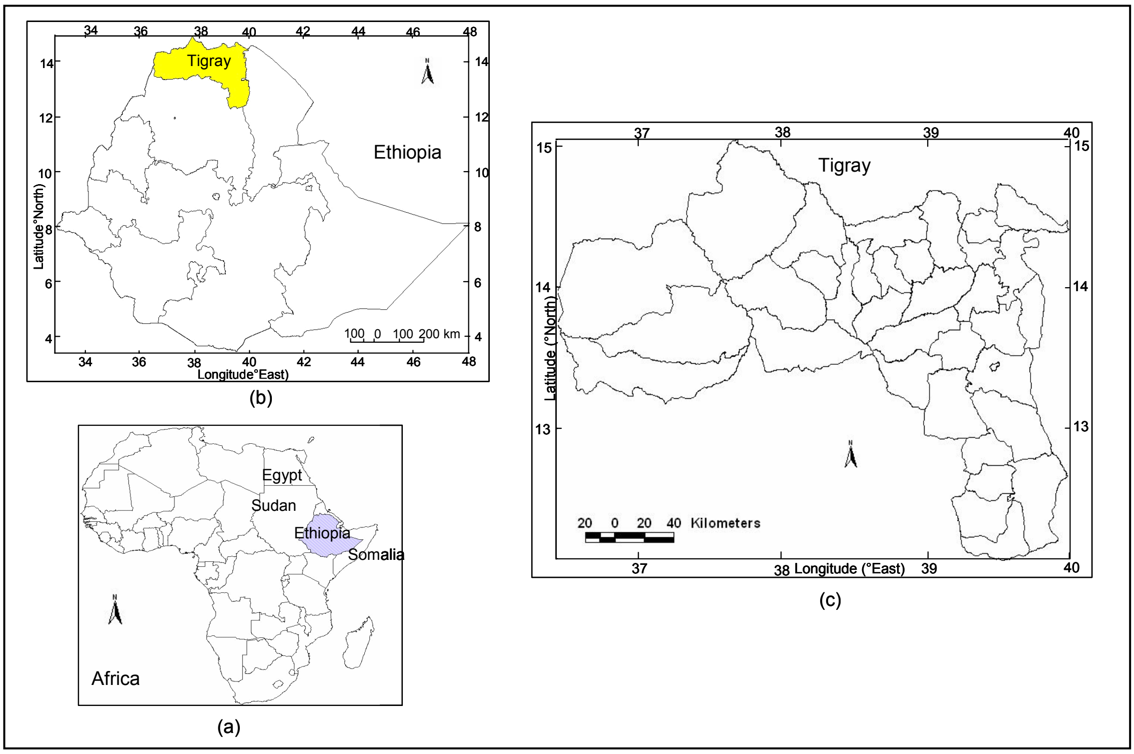


Figure 3.1: Location of study area (a) Africa, (b) Ethiopia, (c) Tigray

3.1.1 Ethiopia: physical attributes and resource potential

Ethiopia is a mountainous tropical country located roughly between 3°- 15°N latitude and 36°- 48°E longitude. The country consists of complex terrain ranging from extreme lowlands of 110 meters below sea level to towering mountains of over 4000 meters above sea level (a.s.l.) (Figure 3.2). Rugged terrain, rolling plains, steep and deep gorges and canyons and extensive plateaus characterize different sections of the country. More than 75% of the country is characterized as upper highlands (elevation more than 2000 meters a.s.l.) with its central part bisected by the northeast-southwest rift valley which is more than 600 kilometers long.

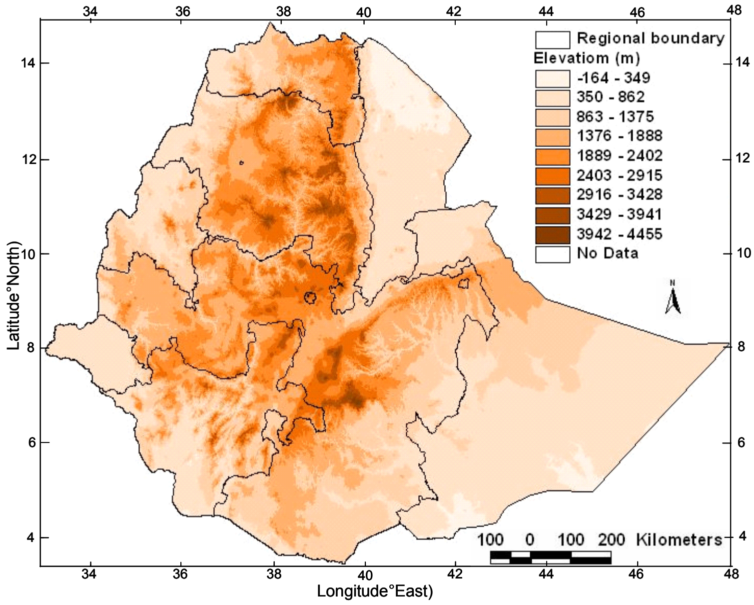


Figure 3.2: Relief of Ethiopia with boundary of the different regions overlaid

The country has a population of over 69 million with an average annual growth rate of 3.2% (CSA, 1998a). Its geographic area is about 112 million hectares of which 60% is estimated to be suitable for agriculture. It is estimated that the country has a potential irrigable area of 4 million ha, of which only 5% is utilized (Gebeyehu, 2002).

The climate of the country is complex, climates from “tropical to subhumid, and subtropical to arctic” occurring within short horizontal distances (Krauer, 1988). Such complexities in climate are the direct reflection of topography, especially altitude and geographical position (Gamachu, 1977; Hellden and Eklundh, 1988). Temperature ranges from a mean annual of above 30 °C to a mean annual of below 10 °C. Generally, precipitation is higher in the southwestern highlands and lower in the coastal lowlands, with average values around 2000 mm and 500 mm y^{-1}, respectively (Krauer, 1988). Mean annual precipitation for Ethiopia is calculated to be 938 (± 83) mm y^{-1} based on 241 stations (Abebe and Apparao, 1989). Different parts of the country experience rainfall in different seasons (Figure 3.3). Most parts of the country receive rainfall during summer months (June to August).

The northwestern and southeastern highlands of the country are the main water sources of the large rivers. The country has more than 12 large rivers with a huge runoff potential, most of them crossing the boundary of the nation. Some of the rivers are used for hydroelectric power generation, while a few are used for irrigation purposes.

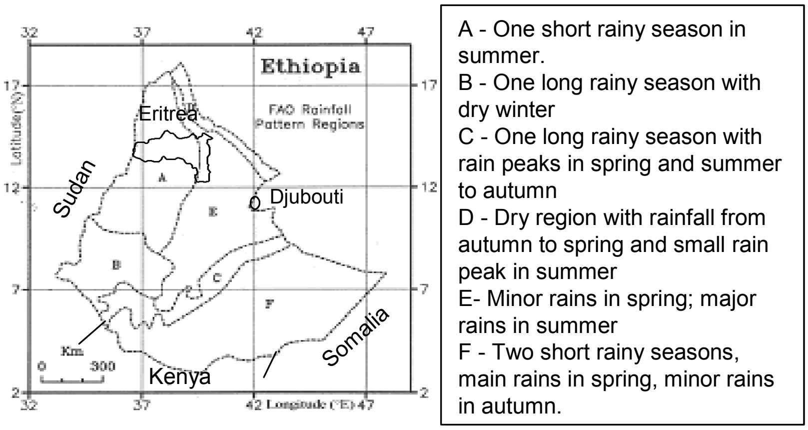


Figure 3.3: Spatio-temporal distribution of rainfall in Ethiopia. Note that Eritrea was part of Ethiopia before 1991 (Source: FAO, 1984a)

Vegetation types in Ethiopia are the direct reflections of altitude, which influences climate (Gamachu, 1977). The major vegetation types range from montane evergreen forest in the southwest and scattered bushes and shrubs in the lowlands to dominantly barren land in some of the coastal deserts.

The wide range of topographic and climatic characteristics, parent material and land use have resulted in extreme variability of soil types in Ethiopia (FAO, 1984a, b). Complex soil forming factors have primarily influenced the distribution of soil types. The main soil types are lithosols, nitosols, cambisols and regosols (FAO, 1984a, b).

The highlands of the country support most of the population, as they offer a favorable environment for human settlement (Sonneveld and Keyzer, 2003). Moreover, the volcanic parent material supplies a rich diversity of nutrients that makes the soils more suitable for agriculture than those in most parts of Africa (Voortman et al., 2000 cited in Sonneveld and Keyzer, 2003). The environmental conduciveness of the highlands along with the relatively fertile soils attract people (88% of the total population), yielding an average population density of 144 persons km^{-2} (Sonneveld and Keyzer, 2003). Under current agricultural production techniques, this largely exceeds the land’s carrying capacity (Higgins et al., 1982). Livestock density, the largest in Africa and ninth in the world, is also concentrated in the highlands, where over 86% of the total livestock population is managed with an average stocking rate of 160 tropical livestock units (TLUs) km^{-2} (Sonneveld and Keyzer, 2003), whereas the recommended densities are in the range of 7-19 TLU km^{-2} for semi-arid to arid areas (Jahnke, 1982 cited in Sonneveld and Keyzer, 2003).

3.1.2 Tigray: physical attributes and resource potential

The Tigray region lies roughly between 12°00' - 15°00' N latitude and 36°30' – 41°30' E longitude (Figure 3.1). The region has an approximate area of 80,000 km^2 with a total population of 3.6 million and an average population growth rate of 2.9%. The average population density of the region is about 72 persons km^{-2}, which exceeds the country's average population density of about 49 persons km^{-2} (CSA, 1998b).

Most people in the region lead a subsistence agrarian life. Agricultural crop production has the oldest history in this part of the country (De Contenson, 1981). Environmental deterioration caused a decline in production which, together with the population increase, created a shortage of land. These processes further led to an expansion of agricultural and grazing activities into marginal and steep slopes, which accelerated environmental deterioration (Gebre-Egziabher, 1989).

The topography of the region is very rugged, comprising both high mountains and incised deep gorges. Altitude varies from about 500 m a.s.l. to 4000 m a.s.l. with a significant proportion of the region having an altitude of more than 2000 m a.s.l. There are several escarpments in the region falling from over 3000 m a.s.l. steeply to below 500 m a.s.l. Terrain slope generally ranges from more than 60% in the central and southern parts to less than 2% in the western lowlands.

According to Mohr (1963), the geological setting of the northern Ethiopian highlands is the result of complex geodynamic processes, which have involved the horn of Africa since the Precambrian. The geology of the region is formed by a Precambrian basement complex, composed of weakly metamorphosed rocks, which are extremely folded and foliated. The predominant rock types are greenstones of basic volcanic origin, but slates and phyllites of sedimentary origin and granites are also common.

The main soil types in the region are reflections of relief. In an ideal type of sequence, soils developed on different elements of the slope can be differentiated. Deeply weathered residual soils are mostly found on the level upper plateaux, while rocky or very shallow soils are dominantly located on the steep scarps. Finer textured soils are more concentrated on the moderately undulating slopes, and deep alluvial soils are found on the level terraces and lower parts of alluvial fans. Generally, leptosols are considered to be more common on the upper slopes, cambisols on intermediate positions and vertisols on lower slopes (FAO, 1984a, b).

Rainfall is highly variable spatially as well as temporally. Annual rainfall ranges between roughly 250 mm and 1000 mm from east to west. The coefficient of variation in annual rainfall in the region is about 20 - 40 % (CoSAERT, 1994; Belay, 1996). Rainfall intensity is generally very high, on average 60 % of the precipitation falls at rates exceeding 25 mm h^{-1} (Virgo and Murno, 1978). The major rainy season is summer with minor rains during spring in some parts of the region. The average temperature in the region is about 18°C, but varies greatly with altitude and season.

The highlands of Tigray have significant amounts of runoff and high irrigation potential (CoSAERT, 1994). However, the economic conditions and complex topography make it difficult to realize the existing potential. Since the rivers flow in gorges (sometimes as deep as 1 km) and originate from a predominantly higher topography with high flow energy, their potential for irrigation within the highlands is limited. Harvesting such high runoff potential is, therefore, considered an alternative to supplement the rainfed agriculture with small-scale irrigation.

In the Tigray region, environmental degradation is one of the highest in Ethiopia. Due to population growth, deforestation and repeated drought, the region has virtually lost its forest cover, and left with only remnant vegetation of an estimated 0.3% (CoSaERT, 1994). The present natural vegetation cover comprises of sparse woodland of thorny acacia bushes and scrubs interspersed between cultivated areas. The combination of rugged terrain, which is sensitive to erosion as well as difficult for utilization and management, poor surface cover and the prominent gullies have led the region to be considered one of the most degraded and degrading (Eweg et al., 1997).

3.2 Methodology

3.2.1 Site selection

Due to time and financial constraints, it was not possible to study all reservoirs with siltation problems in appropriate detail. It was therefore necessary to select sites representative of catchments in the region (Figure 3.4).

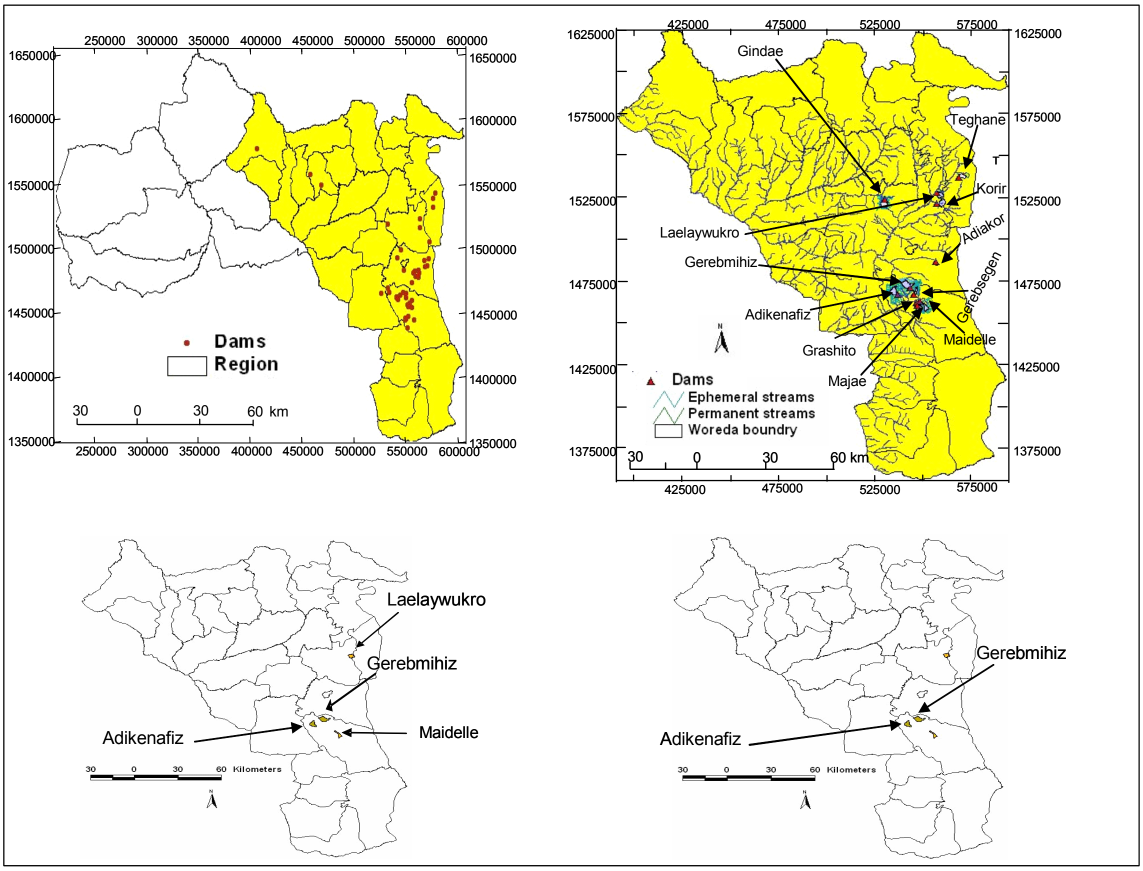


Figure 3.4: The location of reservoir-catchments (top left) 50 sites from which the screening started; (top right) 11 sites for which quantitative sediment deposit data was collected; (bottom left) 4 sites for which erosion/deposition modelling was performed, and (bottom right) 2 sites for which spatial simulation was carried out

Out of about 50 reservoirs in the region, 25 were identified based on their accessibility. The 25 dam sites were then classified by local and regional experts into three categories of siltation (high, medium, low). In addition, field surveys were carried out to characterize the 25 catchments in terms of terrain, LUC types, lithology, and erosion intensity. From the 25 catchments, sites that represent the three levels of siltation categories as well as with different levels of terrain complexity, LUC and lithologic types were selected. Practical conditions to carry out reservoir surveys, i.e., either those with dry-bed or which are filled with water and allow boat based surveys were also basis of site selection. Considering the above issues, 11 sites were selected for quantitative reservoir siltation assessment. Among the 11 sites, 4 were selected for modelling erosion/deposition processes and identifying landscape positions that are more susceptible to erosion. These sites represent high, medium and low siltation rates based on the reservoir survey data. Finally, 2 catchments were selected for LUC-redesign based spatial simulation. These represent those with severe siltation and soil loss problem based on the reservoir survey data and the results of the models. Table 3.1 gives basic morphometric properties of reservoirs of the selected sites.

Table 3.1: Some basic characteristics of the studied reservoirs in Tigray, N. Ethiopia

Site name	DH (m)	DCL (m)	SW (m)	NPL (m^3)	DS (m^3)	PI (ha)
Adiakor	18	210	1.3	n.a.	6008	30
Adikenafiz	15.5	420	10	650000	129000	60
Gerebmihiz	17.5	365	15	719278	141000	80
Gerebsegen	14.9	208	8	n.a.	22400	24
Gindae	19.5	483	23	530000	37878	54
Grashito	9	477	2	142200	17936	12
Korir	15	505	30	1980000	532100	100
Laelaywukro	14.3	660	15	601678	30000	50
Maidelle	15	486	n.a.	1583100	40000	90
Majae	13.5	266	n.a.	n.a.	n.a.	14
Teghane	11	n.a.	n.a.	898190	60000	60

DH = dam height; DCL = dam crest length; SW = spillway width; NPL = normal pool level (live storage capacity); DS = dead storage capacity; PI = potential irrigable land; n.a. = data not available. (Source: CoSAERT unpublished documents/reports)

After appropriate site selection, acquisition of relevant data and analysis of the data were performed to address the stated objectives (Section 1.2). Figure 3.5 shows the methodological approaches employed to assess reservoir siltation, analyze causes, identify sources areas and possible measures of management. Detailed descriptions of the data collection and analysis methods are given in the specific chapters.

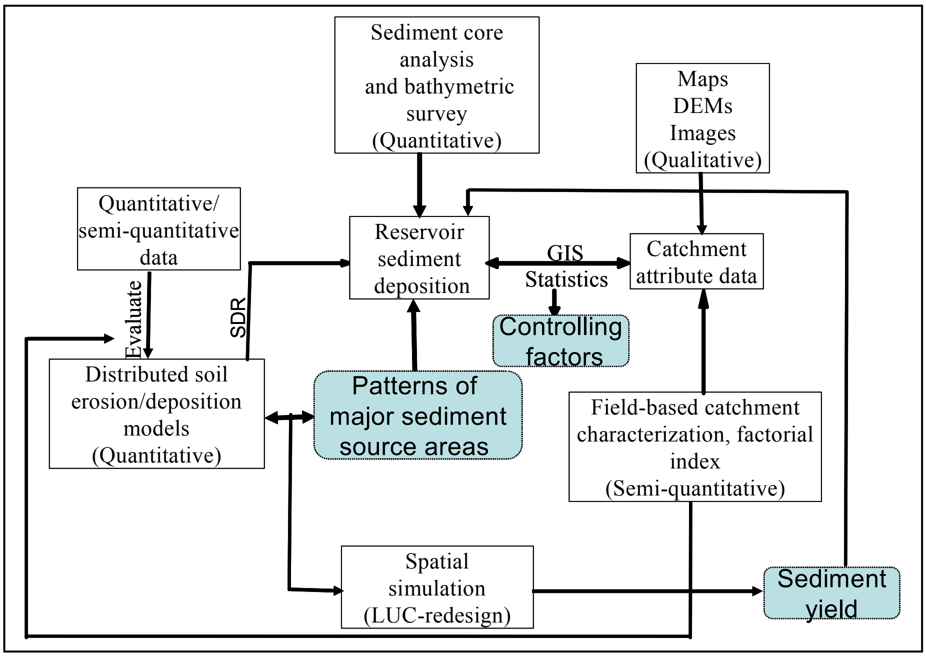


Figure 3.5: Methodological approaches to assess sediment deposition in reservoirs, distribution of major sediment contributing areas, and the impacts of different LUC-redesign scenarios

3.2.2 Constructing Digital Elevation Models (DEMs)

Topography defines the effects of gravity on the movement of water in a watershed and therefore influences many aspects of the hydrological system (Wolock and McCabe, 1995). Terrain geometry and characteristics (slope, aspect, and curvatures) have significant impacts on the spatial distribution of erosion/deposition processes (Moore and Burch, 1986; Desmet and Govers, 1996a; Mitasova et al., 1997). It is therefore essential to take account of the three-dimensional complex terrain through a landscape-based approach to fully capture the spatial distribution of erosion/deposition processes (Mitasova et al., 1998a).

Terrain attributes can easily be derived using GIS and other associated hydrological models provided that sufficiently detailed DEMs are available. Since there were no DEM data covering the study catchments, they were constructed from existing contour maps of scale 1:50000. Topographic maps covering the studied catchments were acquired and scanned[5] from which contours, streams, and spot heights were digitized. DEMs were then constructed for each catchment (Figure 3.6) using the

[5] Scanning of the topographic maps was required, since direct digitizing of contours from the digitizing table was very difficult especially for catchments with steep slopes and complex terrain.

TOPOGRIDTOOL of ARC/INFO (Hutchinson, 1989) from the digitized contours, streams and spot heights.

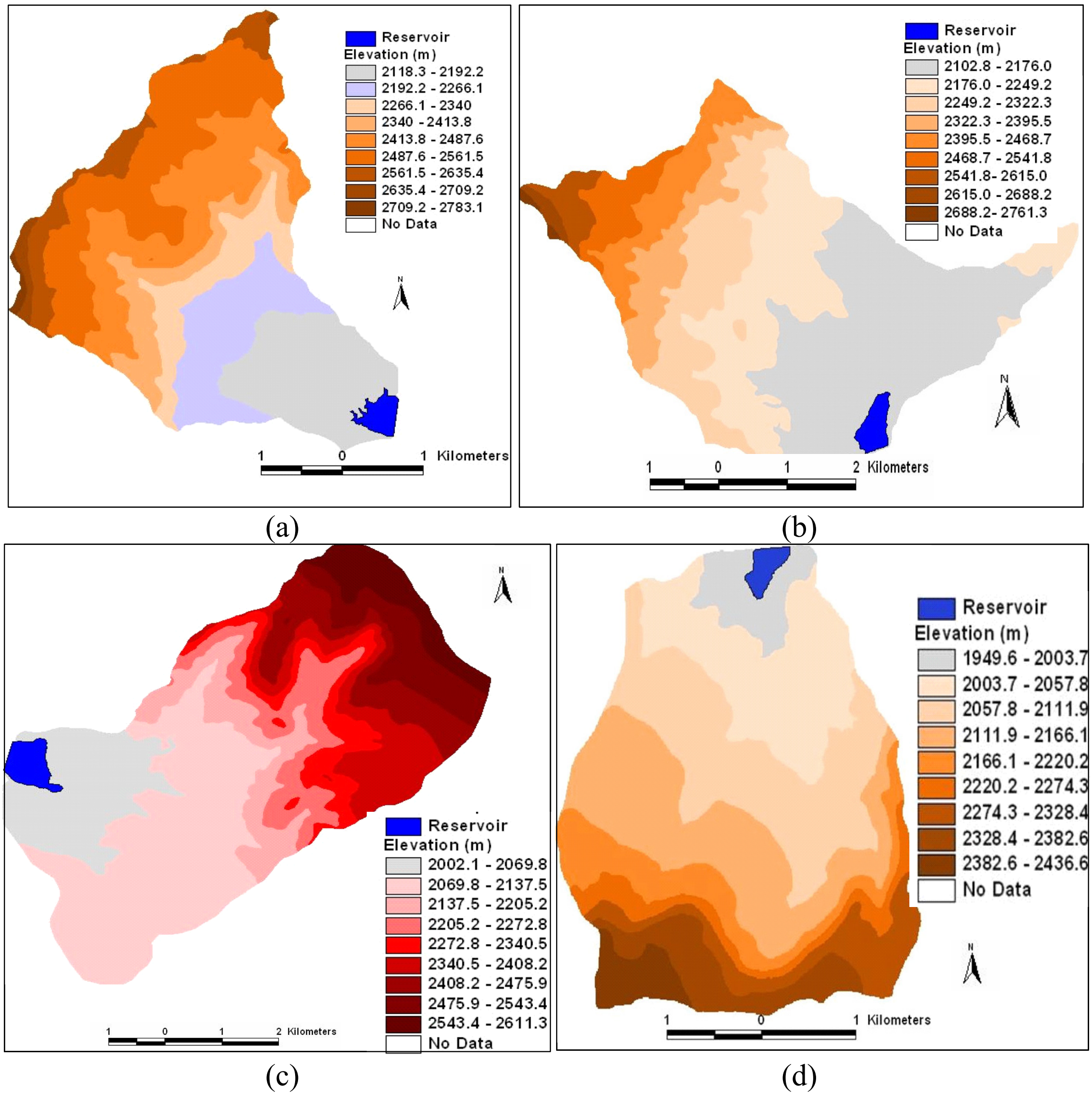


Figure 3.6: DEMs of example catchments (a, Adikenafiz; b, Gerebmihiz c, Korir; and d, Gindae) in Tigray, N. Ethiopia

DEM resolution and cell-size can have a profound effect on the magnitude and spatial patterns of computed topographic attributes and resulting landscape processes (Wilson and Gallant, 2000). The grid-size of DEMs depends on the objective at hand and should match the terrain-dependent hydrological processes (Hutchinson and Gallant, 2000). Zhang and Montgomery (1994) suggested that a 10 m grid size may be a rational compromise between increasing resolution of grid size and the data volume needed for hydrological process modelling. Quinn et al. (1991) also suggested a grid size of 10 m after comparing different grid sizes to validate a terrain-based hydrological model prediction. Considering the original spacing of contours of most catchments (20 m) and in order to obtain a reasonably detailed representation of terrain parameters and their derivations, the DEMs for this study were interpolated at 10 m gird cell size.

Flow tracing can be difficult if DEMs have low accuracy, insufficient vertical resolution and numerous pits that trap the flow lines (Martz and Garbrecht, 1992). Standard algorithms for flow tracing, which use only a limited number of flow directions from each grid cell, can lead to various unrealistic situations, such as prevailing flow in the direction parallel to the x or y axis or diagonals (Fairfield and Leymarie, 1991). Recently, significant improvements in the computation of DEMs from digitized contours have been achieved by applying the spline function with drainage enforcement (Hutchinson, 1989) and by the computation of DEMs using the regionalized spline with tunable tension and smoothening (Mitasova and Mitas, 1993; Mitasova et al., 1995). In this study, the spline function with the drainage enforcement interpolation facility in the TOPOGRID was applied to compute hydrologically correct DEMs with minimum sinks (Hutchinson, 1989). After DEMs were created for all sites, pits/sinks were also filled before any processing was undertaken in order to “route” runoff to the catchment outlet without facing “unnecessary obstacles”.

3.2.3 Deriving land-use and land-cover (LUC) types

Erosion and siltation are mostly enhanced due to human interferences in LUC. LUC data are therefore basic ingredients of erosion models. ASTER images acquired for November/December 2001 were used to derive LUC maps of catchments.

The satellite images were first georeferenced using topographic maps and GPS points. Spatially representative ground control points were identified for georectification, and the images were rubbersheeted to match the ground control points. In all cases, root mean square error (RMS) of less than 6 m was achieved.

Because of the “patchiness” of fields (Figure 3.7) and the relatively similar reflectance between degraded grazing areas and cultivated fields, different enhancement and transformation (NDVI, SAVI, TSAVI, PCA)[6] techniques were used to enhance the separability of cover types and delineate training areas. Once training areas were

[6] NDVI = normalized difference vegetation index; SAVI = soil adjusted vegetation index; TSAVI = transformed soil adjusted vegetation index; PCA = principal component analysis.

delineated based on field data collected using GPS points, the maximum likelihood supervised classification algorithm in IDRISI (Eastman, 2001) was performed on the ASTER bands 1, 2, 3, and PCA-1 images. For catchments with a small area and relatively uniform cover type, field surveys using GPS and aerial photographs were used to delineate LUC types.

Figure 3.7: Cultivated field intermixed with bush/shrub cover in Tigray, N, Ethiopia, Tigray. The light-gray areas (except the stream bed) are cultivated fields, while the dark-gray ones are bushes/shrubs

3.2.4 Field-based catchment characterization

After appropriate site selection and acquisition of elevation and LUC data, different approaches were employed to acquire relevant data. Field surveys were employed to characterize catchments in terms of different attributes such as gully erosion, lithology, level of degradation, and other related factors/processes. Ranking and scoring approaches were employed and evidence photos were taken when necessary. The field survey approaches and respective attributes/processes evaluated are discussed in the respective chapters.

3.2.5 Reservoir survey

Quantitative survey was conducted for 11 reservoirs to estimate their annual rate of siltation. A pit-based survey was conducted for 6 reservoirs with dry-beds while a bathymetric survey was conducted for 7 reservoirs, which were filled with water all year round. 2 reservoirs were surveyed using both approaches to check consistency of the methods. The data were analyzed to estimate annual and area-specific sediment yield of catchments (Figure 3.8). A detailed description of the approach is given in Chapter 6.

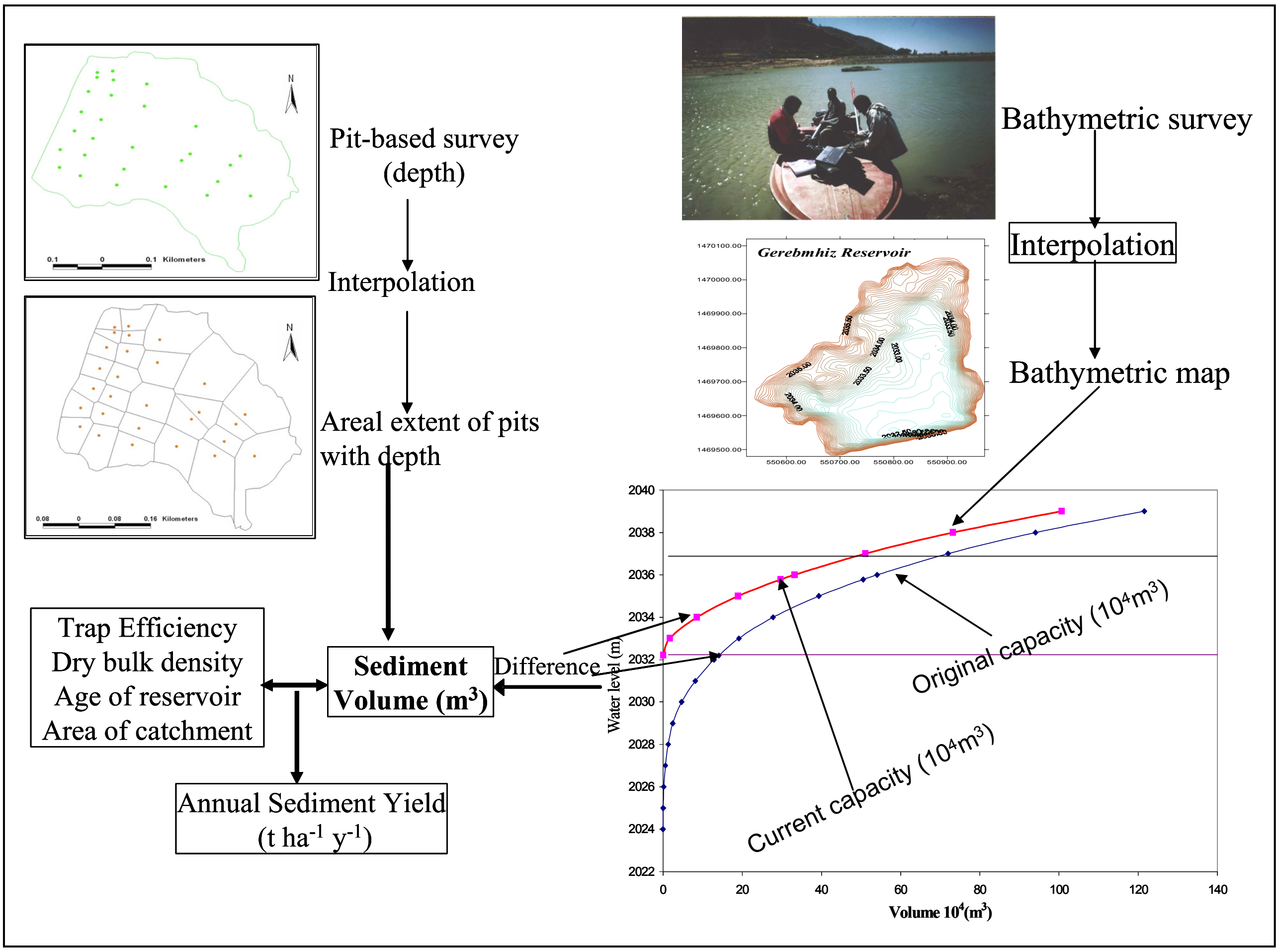


Figure 3.8: Procedures employed to estimate sediment yield based on reservoir survey in Tigray, N. Ethiopia

3.2.6 Modelling spatial patterns of erosion/deposition processes

Three terrain-based models, which do not require too many parameters and detailed calibration, but which have an adequate theoretical basis incorporating basic erosion factors, were selected. The models incorporate terrain complexity as a primary factor in dictating erosion and erosion/deposition processes and can easily be integrated in a GIS environment in a distributed form. The models used were the Stream Transport Capacity Index (STCI), USLE2D and Unit Stream-based Erosion/Deposition (USPED) (Chapter 6). The three models were applied in four catchments to predict rates and spatial patterns of erosion and erosion/deposition[7]. The aim was to identify landscape

[7] In this study, when erosion and erosion/deposition are used, erosion refers to the STCI and USLE2D models which do not consider deposition while erosion/deposition represents the USPED model which predicts both erosion and deposition.

positions that are more susceptible to water erosion and require prior conservation measures. Quantitative (reservoir sediment deposit, ^{137}Cs and soil profile depth) and semi-quantitative (field characterization) data were used to assess the capability of the models to predicting the rates and spatial patterns of erosion and erosion/deposition processes.

3.2.7 Simulation based on LUC redesign approach

After the rates, possible causes and major sediment source areas were defined, measures that can reduce the rate of soil loss and its associated downstream delivery were assessed. In this study, a LUC-redesign approach was employed to assess the impact of reorganizing LUC to reduce soil erosion and sediment delivery. The LUC-redesign focused on enclosing areas that are sensitive to erosion than others. When identifying the landscape positions to be enclosed, different sets of criteria such as gullies, slope and soil loss rate were used.

Once the criteria were set, three categories of spatial scenarios were carried out. Gullies and their 25 m buffer were terraced and grassed while areas above a threshold slope steepness of more than 15 and 25 % were "covered with forest". Areas with soil loss rate of more than 25 and 50 t ha^{-1} y^{-1} were also taken out of cultivation and afforested. As many as ten scenarios, including existing condition, were simulated and the resulting soil loss reduction analyzed. A distributed erosion/deposition model (USPED) was used to simulate the different scenarios. Chapter 7 discusses details and results of this approach.

4 RESERVOIR SILTATION: RATE OF SEDIMENT YIELD AND ITS RELATION WITH CATCHMENT AREA

4.1 Introduction

In many developing countries, sustainable land management and water resources development are threatened by soil erosion and sediment-related problems (Morris and Fan, 1998). In Ethiopia, accelerated siltation of reservoirs that are intended to provide irrigation water has resulted in the loss both of the intended services from the reservoirs and of the considerable investments incurred in their construction. The frequent power cuts and rationing-based electric power distribution experienced in the country are also attributed to the loss of storage capacity of hydro-electric power lakes due to erosion (Ayalew, 2002). At the same time, the on-site effect of water erosion, which results in the loss of nutrient-rich top soil and hence reduced crop yields, is chronic in the country. As estimated by Hurni (1993), soil loss due to water erosion from cultivated fields in Ethiopia amounts about 42 t ha^{-1} y^{-1}. An estimate by FAO (1986) also shows that some 50% of the highlands was already significantly eroded, and erosion was causing declines in land productivity at the rate of 2.2% per year. Rate of soil erosion is more severe in the more barren and mountainous Tigray region, some studies estimating erosion rates of more than 80 t ha^{-1} y^{-1} (Tekeste and Paul, 1989).

Despite the fact that catchment erosion is believed to be responsible for the loss of valuable nutrients and rapid storage loss of water harvesting schemes in Ethiopia, there have been few studies to quantify erosion rates and understand the spatial dynamics of erosion-siltation processes on a catchment scale (Zinabu, 1998). Some of the studies related to erosion are based on erosion plots (e.g., SCRP, 2000), which can not be easily extrapolated to basin scale and which are also too few in number to represent the diverse environments of the country (Bewket and Sterk, 2003). Furthermore, some of the sediment yield estimates based on suspended sediment sampling at gauging stations may not be reliable, since measurements are not systematic and continuous (NEDECO, 1997). The spatial scales of measurements in the latter case are also generally coarse with limited potential to be adapted for small catchment scale studies. There is therefore a need to determine the rate of soil loss and sediment yield at scales that can help narrow the missing link between plot- and large basin-based studies (e.g., Verstraeten and Poesen, 2001a). This study is the first attempt in the drylands of northern Ethiopia aimed at estimating sediment yield in catchments of scale (3-20km^2) where different forms of erosion processes and a mosaic of heterogeneous environmental factors are observed.

Sediment-based research will remain a recognized aspect of erosion studies for the foreseeable future due to its successful application to a great variety of problems and environments (Oldfield and Clark, 1990). Different approaches exist to estimating catchment erosion and sediment delivery processes. Distributed physically based models that determine catchment erosion and route the soil along channels to ultimately estimate sediment delivery are becoming popular (e.g., Ascough et al., 1997; Ferro et al., 1998; Van Rompaey et al., 2001). Other approaches to estimating sediment yield are those based on sediment rating curves and river samplings (e.g., Dearing and Foster, 1993; Steegen et al., 2000). The bathymetric survey, which is based on comparing the elevation of the sediment level in a reservoir before impoundment with elevation of existing sediment level (e.g., Rausch and Heinemann, 1984; Juracek and Mau, 2002), is another alternative used to estimate sediment yield. Measuring thickness of reservoir sediment deposits using sediment pits is another possibility of determining sediment yield (Oldfield and Clarke, 1990; Duck and McManus, 1990; Butcher et al., 1993; Dearing and Foster, 1993; Schiefer et al., 2001; Erskine et al., 2002). Among the aforementioned approaches, reservoir sedimentation surveys (bathymetry and pit-based) seem to be appropriate for Ethiopian condition in terms of cost, speed and applicability. Verstraeten and Poesen (2000) indicate that dam sedimentation surveys can be used to map sediment yield estimates and identify areas of high soil loss risk at relatively low cost. Butcher et al. (1992) highlights that in contrast to stream sampling or plot and pin measurement, reservoir surveys are relatively simple requiring only short field surveys. Stott et al. (1988) argue that reservoir survey methods are more useful and representative because measurements of sediment deposit do not involve generalized statistical models of sediment erosion and transport or spatial extrapolation of point and plot measurements. Besides, it is shown that data derived from simple studies of reservoirs can provide a more reliable indication of sediment loss within the catchment than may be obtained from gauging stations and rating curves (Walling and Webb, 1981; Al-Jibburi and Mcmanus, 1993; Einsele and Hinderer, 1997). Considering the above issues, pit-based (dried-up reservoirs) and bathymetric (reservoirs filled with water) surveys were used in this study to estimate sediment deposition in reservoirs.

Sedimentation surveys cannot be easily applied in developing areas and remote regions. Such areas, however, require prior attention in resource monitoring and management to sustain their resource potential. There is, therefore, a need to extrapolate results obtained at one location to another location of similar scale and environment. Currently, most sediment yield predictions are achieved through simple empirical models that relate the annual sediment delivery by a river to catchment properties including drainage area, terrain, land use and land cover (LUC), lithology and climate (Hadley et al., 1985; Verstraeten and Poesen, 2001a; Verstraeten et al., 2003). Catchment area is probably the most important of all variables that can be used to predict area-specific sediment yield (Lahlou, 1988).

The relationship between annual sediment yield and catchment area, however, depends on the complexity and variability of associated terrain attributes such as topography, LUC, soils and climate. This means that the sediment delivery of catchments of similar size could be completely different if they have contrasting climate and geomorphologies (Verstraeten et al., 2003). This shows the need to evaluate the relationship between catchment area and measured area-specific sediment yield (SSY) for local conditions before attempting to adopt empirical relationships established in other environmental settings (De Boer and Crosby, 1996; Schiefer et al., 2001).

This study aims to (1) estimate the rate and magnitude of sediment deposition in reservoirs, and (2) examine the relationship between catchment area and annual sediment yield in the region. Results related to the magnitude and rate of sediment yield could help to prioritize areas of intervention based on differences in the severity of cases. The established SSY-area relationship, if significant, could help to predict SSY for other sites with similar environmental settings.

4.2 Study area and site characteristics

4.2.1 Site selection

Catchment erosion and sedimentation are functions of terrain, LUC and management, and soil characteristics. To account for the role of differences in these factors, 11 representative sites in the region were selected in Tigray, N.Ethiopia, (Figure 4.1). Field visit was conducted in June – August 2002 to select sites with heterogeneous attributes such as terrain, LUC, surface lithology and intensity of erosion processes such as gullies. Besides terrain attributes, the existing conditions during the field surveys (whether reservoirs were totally dry or whether those that were filled with water were large enough to allow boat-based surveys) were the basis of site selection. In addition, reservoirs with original area-capacity curve (reservoir–bed topography) data were selected for the bathymetric survey. Major catchment attributes used as basis of site selection are shown in Table 4.1.

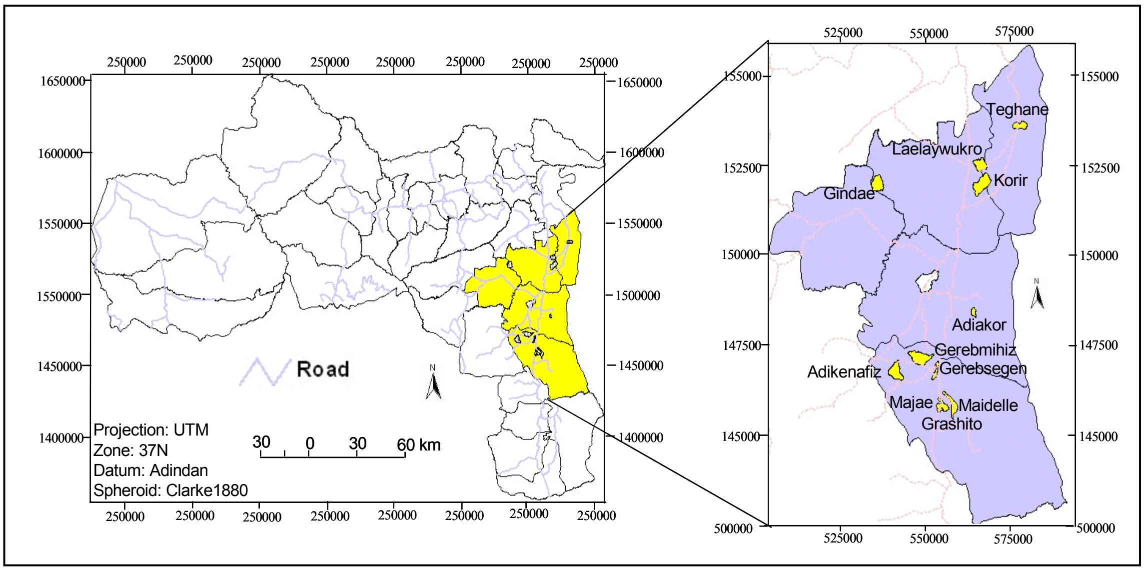


Figure 4.1: Spatial distribution of study sites in Tigray, N. Ethiopia

4.3 Materials and methods

4.3.1 Assessment of reservoir siltation

Two methods of quantifying sediment deposition in reservoirs were applied: sediment-pit analysis and bathymetric survey. The former was used for reservoirs with a dry bed while the latter was used for reservoirs that were filled with water and allow boat-based survey. To compare the results, 2 reservoirs were surveyed using both approaches (Table 4.2). The procedures followed to derive sediment yield estimate from reservoirs based on the two methods are described below.

Table 4.1: Major catchment attributes used during preliminary site selection in Tigray, N.Ethiopia

Name of site	Catchment area (km^2)	Terrain form[a]	Land-use/cover[b]	Surface Lithology[c]	Gully erosion[d]
Adiakor	2.8	Medium	Cultivated	Limestone/shale	Low
Adikenafiz	14.0	Complex	Cultivated	Limestone/shale	High
Gerebmihiz	19.5	Complex	Cultivated	Limestone/shale	High
Gerebsegen	4.0	Simple	Cultivated	Shale	Medium
Gindae	12.8	Complex	Bush/shrub	Shale/marl	High
Grashito	5.6	Simple	Culttivated	Shale	High
Korir	18.6	Complex	Bush/shrub	Sandstone/marl	Medium
Laelaywukro	9.9	Complex	Bush/shrub	Sandstone	Medium
Maidelle	10.3	Medium	Cultivated	Shale	Medium
Majae	2.8	Simple	Cultivated	Limestone/shale	Low
Teghane	7.0	Medium	Cultivated	Metavolcanics	Low

Note: The terrain attributes above are intended to show ***relative differences*** *between sites based on field surveys and do not mean that only the indicated attribute prevails in the respective sites.*

[a] *Field visit was carried out in June 2002 to select sites with heterogeneous terrain configuration so that catchments of both "simple", "medium" and "complex" terrain were included. Field observation was conducted to visually evaluate terrain slope and curvature.*

[b] *Despite the fact that most catchments have a high proportion of cultivated land, sites with relatively better bush/shrub cover and enclosure/protected areas were also identified.*

[c] *Catchments with different lithologic types were selected to evaluate the effect of lithology on sediment yield variability. Field visit, lithology maps, and aerial photographs were the basis for classifying catchments into different lithologic types.*

[d] *Gully erosion and bank collapse contribute sediment to reservoirs and increase catchment connectivity, facilitating sediment delivery. Those catchments with different levels of gully erosion and bank collapse were selected based on aerial photographs and field survey.*

4.3.2 Estimating reservoir sediment deposit based on sediment pit data

This method is based on measuring the thickness of the sediment deposit within the reservoir. Sediment depth thickness measurements for six dried-up reservoirs (Table 4.2) were conducted in June 2003. Spatially distributed pits were opened within each study reservoir. Number of points sampled range from 11 to 28 depending on size and shape of reservoirs as well as pattern of sediment deposition based on visual observation (Figure 4.2a). Auguring was conducted to measure the sediment thickness (pit-depth). Differentiation between bottom *in situ* material and newly deposited sediment was easy due to sediment stratification.

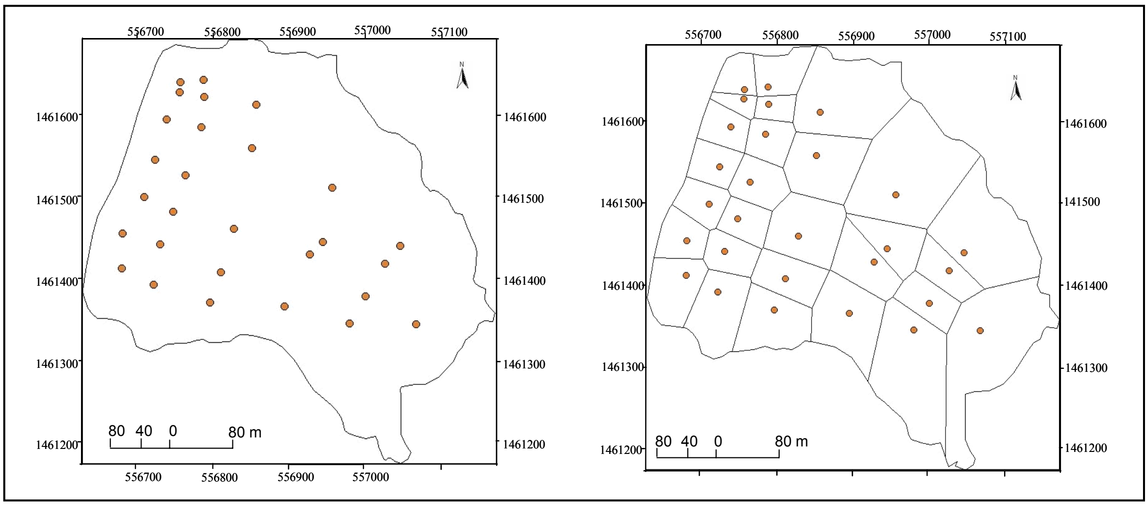


Figure 4.2: Example of (a) the spatial distribution of sediment pits and (b) results of Thiessen polygon interpolation for Maidelle reservoir in Tigray, N. Ethiopia

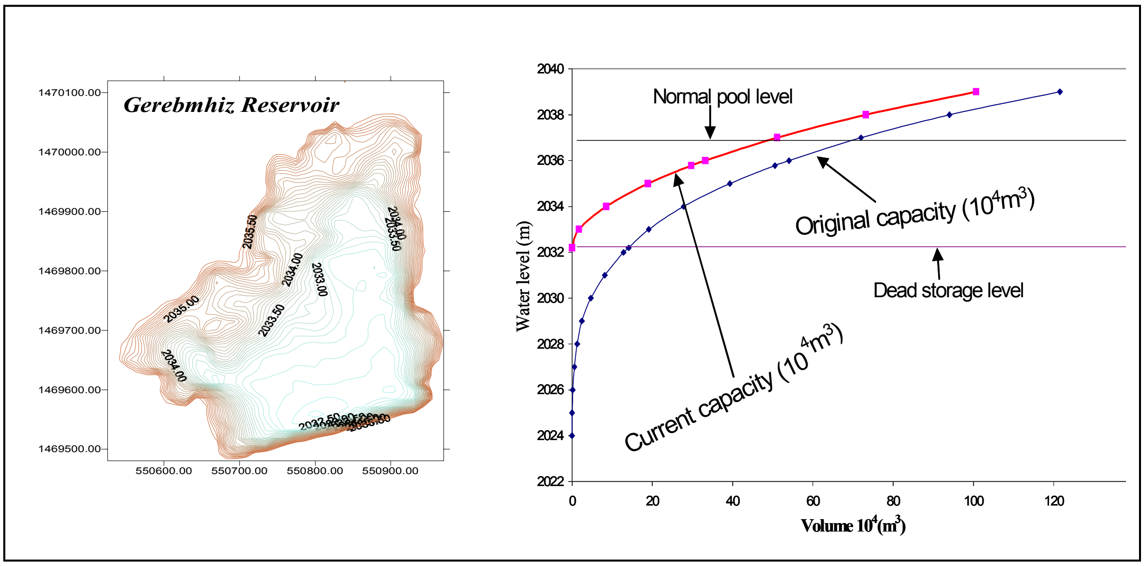
Average sediment thickness per reservoir, Thiessen polygon, and inverse distance weight (IDW) interpolation methods were tested to determine the sediment deposition in the reservoirs. Multiplying average pit-depth with reservoir area may overestimate sediment yield because in reality there is a tendency for sediment deposition to decrease with increasing distance from the embankment of the dam. On the other hand, IDW may underestimate sediment yield, because it assumes a linear decrease in pit depth with increasing distance from the dam embankment towards the inflow, which may not be necessarily true. The Thiessen polygon approach may give a more appropriate estimate of sediment yield compared to the two, since it is based on partitioning the whole reservoir based on "area of influence" of pits (Goovaerts, 2000). Sediment yield based on the Thiessen polygon interpolation method was therefore used in this study (Figure 4.2b). The volume of trapped sediment in each polygon (zone) was determined by multiplying sediment pit depth/thickness (m) by the respective area of each polygon (m^2). The sediment deposit within each polygon was then summed to estimate the total volume (m^3) of sediment trapped in each reservoir.

4.3.3 Estimating reservoir sediment deposit based on bathymetric survey

The bathymetric survey is based on comparing the volume of reservoir capacity at different periods. In this case, information on the original capacity of the reservoirs is required to be used as a benchmark against which the existing storage capacity can be compared (Rausch and Heinemann, 1984). The original storage capacity of the reservoirs was acquired from the Tigray Bureau of Water Resources.

To derive existing storage capacity, bathymetric surveys were conducted in November 2003 for seven reservoirs (Table 4.2) using a small motorboat fitted with a depth-counter and global positioning system (GPS). The GPS was used to record the geographic position of the boat when recording each measurement and a depth-counter was used to determine the depth from the water surface to the top of the sediment. For reservoirs where sediment deposition occurs beyond the water surface level, a land survey was conducted using Total Station to determine current elevation above the sediment. The periphery and elevation of the water surface for each reservoir were also marked out by GPS and Total Station. A systematic approach that enabled the acquisition of well distributed data within each reservoir was followed during the surveys. In order to account for the spatial variability of sediment deposition within reservoirs, more than 700 points covering the whole of the water surface (bathymetry) and to the extent where deposition exists (land survey) were collected for each reservoir. These data were then stored in a computer and analyzed using Surfer Software (Golden Software inc., 2000).

The elevation of the current reservoir bed (top of sediment) at each measurement point was defined by deducting water depth (estimated by depth counter) from current water surface level (measured using Total Station). Bathymetric maps of the existing reservoir bed (Figure 4.3a) were then generated using Kriging interpolation in Surfer (Golden Software inc., 2000). Storage capacity and water surface area of the reservoirs at each 1m interval were calculated using Surfer's "Volume" function, based on which the current area-capacity curves of the reservoirs were constructed. The total volume (m^3) of sediment deposition was then calculated by subtracting current water storage capacity from water storage capacity before impoundment (Figure 4.3b).



(a) (b)

Figure 4.3: (a) Contour map produced from bathymetric survey data and (b) current and original area-capacity curves for one example reservoir in Tigray, N. Ethiopia

4.3.4 Determining dry-bulk density of reservoirs

In order to be able to compare siltation rate of different reservoirs, it is necessary to convert the measured sediment volume (m^3) to sediment mass (ton) using representative dry-bulk density (dBD) (e.g., Butcher et al., 1993; Verstraeten and Poesen, 2001a). Undisturbed wet sediment samples of known volume were, therefore, collected from the six dry-bed reservoirs (Table 4.2). Three samples were collected from each reservoir and were oven-dried at 105°C. The mean dBD of each group of samples was then determined and used to calculate sediment mass. Since it was not possible to collect soil samples from reservoirs filled with water, the average dBD of the 6 reservoirs was used for all 11 sites. The mean dBD for the 6 reservoirs, which is also used for all reservoirs, is 1260 kgm^{-3} with a range of 1160 kg m^{-3} to 1320 kgm^{-3}.

4.3.5 Estimating trap efficiency of reservoirs

Trap Efficiency (TE) is the proportion of the incoming sediment that is deposited, or trapped, in the reservoir (Rausch and Heinemann, 1984; Verstraeten and Poesen, 2000). In order to determine the average sediment yield from the contributing watersheds, the weight of deposited sediment needs to be adjusted for reservoir sediment TE. This helps to make adjustments for the sediment that may leave the reservoir and avoids possible underestimation of sediment deposition (Rausch and Heinemann, 1984).

There are different approaches to estimating TE of reservoirs (e.g., Rausch and Heinemann, 1984; Verstraeten and Poesen, 2000). One of the most commonly used empirical-based models is that proposed by Brown (1943), which is given as (Verstraeten and Poesen, 2000):

$$TE = 100\left(1 - \frac{1}{1 + 0.0021D\frac{C}{A}}\right) \quad (4.1)$$

where C = reservoir storage capacity (m^3) and A = catchment area (km^2). D has constant values ranging from 0.046 to 1 with a mean value of 0.1.

In equation 4.1, the value of TE depends on the value of D, which again depends on reservoir characteristics. Considering the difficulty of objectively defining a value for D and the scarcity of data to employ process-based models (e.g., Verstraeten and Poesen, 2000) , sediment yield estimate based on TE calculated using a D value of 0.1 in equation 4.1 was discussed in this study.

4.3.6 Calculating sediment yield to reservoirs

After the basic parameters necessary to calculate sediment yield were defined, the following equations were used to calculate annual (SY) and area-specific (SSY) sediment yield, respectively:

$$SY_p = 100\frac{(\sum P d_i AT_i) * dBD}{TE * Y} \quad (4.2)$$

$$SY_b = 100\frac{SV * dBD}{TE * Y} \quad (4.3)$$

$$SSY = \frac{SY}{A} \quad (4.4)$$

where SY_p and SY_b = pit- and bathymetry- based sediment yield (t $year^{-1}$), respectively; SSY = area-specific sediment yield (t $ha^{-1}year^{-1}$); Pd_i = the depth of each pit (m); AT_i

= area of Thiessen polygon i around each pit (m^2); *dBD* = dry-bulk density (t m^{-3}); *TE* = trap efficiency (%); *Y* = age of reservoir (years); *SV* = sediment volume calculated from differences of area-capacity curves (m^3); *SY* = annual sediment yield based on either SY_p *or* SY_b*;* *A* = area of catchment (ha) extracted from DEMs using CatchmentSIM (Ryan and Boyd, 2003).

Sediment yield estimation is based on the calculation of different values with possible effects on SSY estimates. SSY estimates considering dBD of the 6 reservoirs and average pit depth and IDW interpolation methods are discussed in section 4.5.

Table 4.2: Basic parameters used for calculating SY and SSY of reservoirs in Tigray, N. Ethiopia

Site	RA (ha)	A (km^2)	C (10^6m^3)	Age (Year)	dBD (t m^3)	TE (%)	Survey method
Adiakor	1.4	2.8	0.51	5	1260	97	Pit-based
Adikenafiz	12.4	14.0	0.67	6	---	91	Bathymetry
Gerebmihiz	15.4	19.5	1.30	6	---	93	Bathymetry
Gerebsegen	1.7	4.0	0.34	3	1230	95	Pit-based
Gindae	7.6	12.8	0.79	5	1320	93	Pit-based
Grashito	8.6	5.6	0.17	5	1320	86	Both
Korir	18.1	18.6	2.00	8	---	96	Bathymetry
Laelaywukro	7.1	10.0	0.85	6	---	95	Bathymetry
Maidelle	16.6	8.7	1.58	5	1160	97	Both
Majae	1.0	2.8	0.30	5	1250	96	Pit-based
Teghane	19.6	7.0	1.80	7	---	97	Bathymetry

RA = reservoir area; A = catchment area; C = gross reservoir capacity; dBD = dry-bulk density of dry-bed reservoirs; TE = trap efficiency (based on Brown's D = 0.1 value of equation 4.1)

4.4 Results

4.4.1 Sediment deposition in reservoirs

The amount and rate of sediment deposition in the 11 surveyed reservoirs is presented in Table 4.3. The sediment deposit data show that SSY ranges from 3 to 49 t ha^{-1} y^{-1} with a mean SSY value of 19 t ha^{-1} y^{-1}. Annual sediment deposition (SY) in each reservoir ranges from 1400 to over 75000 t y^{-1} with a mean deposition rate of over 20000 t y^{-1}.

Due to the wide contrast in environmental variables of catchments such as terrain, lithology, surface cover and gully erosion (Table 4.1), there is relatively high sediment yield variability between catchments with a range of 46 t ha^{-1} y^{-1}.

Table 4.3: Sediment deposition rates in reservoirs derived from sediment pits and bathymetric survey analyses in Tigray, N. Ethiopia

Site name	SV (m^3)	SD (ton)**	SY ($t\ y^{-1}$)	SSY ($t\ ha^{-1}y^{-1}$)
Adiakor	5519	6954	1427	5.0
Adikenafiz	299266	377075	69095	49.4
Gerebmihiz	339200	427392	76320	39.0
Gerebsegen	10550	13293	4681	11.7
Gindae	92208	116182	25022	19.5
Grashito	58000	73080	16909	30.2
Korir	119680	150797	19684	10.6
Laelaywukro	29280	36893	6494	6.5
Maidelle	79540	100220	20569	23.6
Majae	7250	9135	1908	6.8
Teghane	12998	16378	2412	3.4

*SV = sediment volume; SD = sediment deposit (SV*dBD); SY = annual sediment yield; SSY = area-specific sediment yield. **Dry bulk-density (dBD) of 1260 kg m^{-3} is used for all reservoirs based on mean dBD of the 6 dry-bed reservoirs.*

With the above rate of sediment deposition and based on reservoir live storage capacity shown in Table 3.1, most of the reservoirs will be filled with sediment within less than 50% of their projected service time. For instance, the Adikenafiz, Gerebmihiz and Grashito reservoirs have lost over 40% of their live storage capacity within about 25% of their expected service time. These reservoirs and others such as Gindae and Maidelle have also lost more than 100% of their dead storage capacity (designed to store anticipated sediment until design life) in less than a quarter of their expected service time. It is also commonly observed that the outlets of most of the reservoirs are clogged with sediment, which limits irrigation practices (e.g., Adikenafiz, Grashito, Maidelle, and Gindae). Such accelerated loss of storage capacity means that the planned food security improvement scheme will be under threat unless relevant preventive measures are put in place. Rapid failure of reservoirs before the end of their anticipated service time also means a much lower internal rate of return and greater loss of money spent for the construction of the dams, which otherwise would have been invested for other purposes or in another sector of the economy.

If we interpret the annual sediment deposition as a proxy to catchment erosion, it is possible to see that the magnitude of annual soil loss reported in Table 4.3 is generally higher than the tolerable[8] soil loss of 2 – 18 t ha^{-1} y^{-1} estimated for the country (Hurni, 1985). All the erosion estimates in Table 4.3 are above the minimum tolerable limit and five of the catchments have an annual soil loss above the maximum tolerable limit. The soil loss rates shown in Table 4.3 are not only above the tolerable limit but also beyond the rate of soil generation of 3-7 t ha^{-1} y^{-1} (Hurni, 1983a, b). This highlights the significance of erosion on soil loss from upslope and its associated impact on downstream sedimentation.

When the result the mean SSY of 19 t ha^{-1} y^{-1} is put into a global context based on data by Lawrence and Dickinson (1995), it can be seen that the northern highlands of Ethiopia can be grouped with regions experiencing high amounts of sediment yield, the global and African averages being 15 and 9 t ha^{-1} y^{-1}, respectively.

4.4.2 Rate of sediment yield as compared to results of other studies

Studies conducted in the region reported soil loss rates of different amounts. Direct comparison of such studies with the results reported in Table 4.3 may be complicated due to differences in the scale and methods of measurement and processes involved. We therefore only summarized some of the studies conducted in the region based on gauging stations and reservoir surveys in relation to the results reported in this study.

NEDECO (1997) reports compiled SSY estimates conducted at river gauging stations and suspended sediment samplings in the northern parts of Ethiopia. The reported soil loss estimates range from 1.4 t ha^{-1} y^{-1} to about 33 t ha^{-1} y^{-1} for different basin sizes of 15 to 70000 km^2. The SSY estimates reported in (NEDECO, 1997) are largely in agreement with the results reported in Table 4.3. However, since the period and location of measurements as well as the size of the catchments involved are quite different, direct comparison of the results based on the two approaches may not be possible. One major difference between the two is that SSY data reported in NEDECO (1997) are based on measurements made at the lower positions of rivers after they have crossed flat areas and marshes. Higher SSY estimates are expected upstream of gauging stations as slopes become steeper and as a result specific sediment yield is generally high for smaller headwater basins than big streams (Milliman and Syvitsky, 1992). It is also indicated that interpretation of the data compiled by NEDECO, especially

[8] "Tolerable soil loss"(T) denotes the maximum rate of soil erosion that can occur and still permit crop productivity to be sustained economically (Renard et al., 1997).

comparing to results of other studies, requires caution, as sampling was not continuous and monitoring not well structured (NEDECO, 1997).

Machado et al. (1995) estimates an SSY of 21 t ha^{-1} y^{-1} based on an in-filled dam with a catchment area of 6.7 km^2 on one of the Tekezze River's tributaries in the Tigray region. This result can be considered in general agreement with those reported in Table 4.3 considering the similarity of scale of measurement.

Table 4.4 shows SSY results of other studies conducted in the region based on reservoir pit-based surveys. The studied sites are of similar age and size to the ones reported in this study and the measurement techniques are similar. One of the reservoirs, Grashito, was also surveyed three different times, including this study. From Table 4.4, it can be seen that SSY estimates related to the Grashito reservoir are generally higher than those observed in our study.

Table 4.4: Reservoir sedimentation survey based on sediment pit approach (Gebre-Hawariat and Haile, 1999; Aynekulu et al., 2000)

Reservoir	**Catchment (km^2)**	**SSY t ha^{-1} y^{-1}**	**Total deposit (ton)**
Fliglig	6.12	24.0[1]	
	6.12	17.0[2]	
Grashito	4.46	**63.0[1]**	28145.3
	4.46	**40.0[2]**	35961.2
	5.56	**30.0[3]**	16909
Maiserakti	4.48	19.0[1]	
HW. Cheber	30.00	25.0[1]	

[1] *Survey was conducted within one year of reservoir construction (Gebre-Hawariat and Haile, 1999).*
[2] *Survey was conducted after two years of reservoir construction (Aynekulu et al., 2000)*
[3] *Is based on result of this study; dBD of 1500 kg/m^3 is assumed during calculation in the two cases while 1260 kg/m^3 is used in this study. TE of 100% is considered for the two studies*

The SSY estimates made immediately after the construction of the reservoir show the highest yield followed by those measured after successive years of age. This can be due to temporal variation in conservation practices introduced after dam construction. However, such were not observed in the study sites shown in Table 4.4.

Another reason could be due to temporal variation in the amount of rainfall between survey periods. The rainfall data between the years 1997/98 and 2002/2003 shows that rainfall was high just after construction (1998 summer), which might have increased runoff and accelerated soil erosion and transport. Actually, the rainfall during this year was the second highest since 1972 excluding the periods where no rainfall data were available (Figure 4.4). The sediment yield data collected after one year of the first survey (Aynekulu et al., 2000), which was just after a low rainfall season (Figure 4.4), shows that the SSY estimates are about 35% less than the first survey.

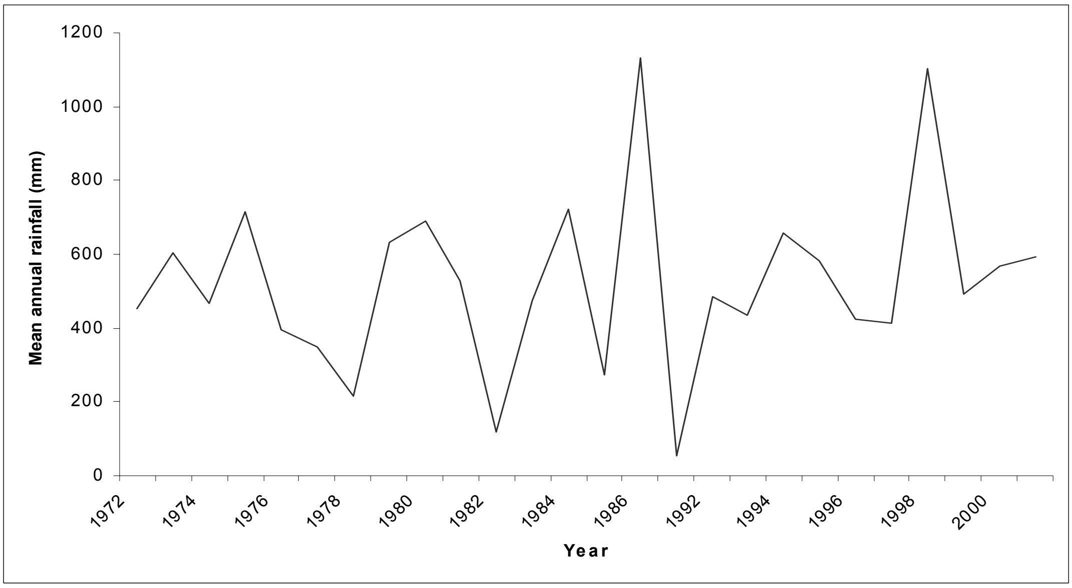


Figure 4.4: Mean annual rainfall of Adigudom station (within about 3 km of Grashito reservoir) in Tigray, N. Ethiopia. Note that rainfall data for the years 1987 to 1991 were not available

The values used for dBD, TE, catchment area, effective reservoir area and the spatial distribution and number of sediment pits considered could also affect the SSY estimate. For instance, the results reported in Table 4.3 are based on a dBD value of 1260 kg m^{-3}, while those of Table 4.4 used a dBD value of 1500 kg m^{-3}, which could result in slightly different SSY estimates. The two studies also employed TE of 100% while this study estimates TE of 86% for the same reservoir, which can slightly increase SSY estimate. In addition, the results in Table 4.4 are based on a catchment area of 4.5 km^3 (Grashito reservoir), while the catchment area calculated in this study is 5.6 km^2, which could affect the final SSY estimates. For instance, if the sediment deposit estimates (m^3) made for the Grashito reservoir by Gebre-Hawariat and Haile (1999) and Aynekulu et al. (2000) are used and the SSY is calculated based on the dBD and catchment area used in our study, the SSY values reported by the two studies for the Grashito reservoir would be lowered to 43 t ha^{-1} y^{-1} and 27 t ha^{-1} y^{-1}, respectively. This reduces the gap between the three surveys, and the still relatively high value in the first study could be caused by the high rainfall that preceded the survey.

The relatively inflated SSY estimates in the two surveys could also be explained by the fact that the reservoirs are still functioning, at least partially, despite the fact that they were predicted to be out of function. For instance, Gebre-Hawariat and Haile (1999) and Aynekulu et al. (2000) predicted that the lifetime of the Grashito reservoir would be another 3 and 4 more years after the respective survey periods. Thus, the reservoirs should have been completely dry by the year 2002 and 2003, after the two respective surveys. However, this was not the case as observed during a boat-based bathymetric survey on the same reservoir in November 2003.

Finally, there is a general tendency that rate of siltation is higher during the early stages of an impoundment and shows a relative decline at later stages. During early stages there is wide and deep depositional sink which can encourage rapid water and sediment flow from nearby the dam and upslope areas while after years of sediment deposition the reservoir-bottom could be reshaped into gentle and flat surface which may result in slower runoff and sediment flow (Soler-Löpez, 2001). This could result in a slightly reduced rate of siltation over time which could cause differences between the three surveys.

4.5 Discussion

4.5.1 Factors influencing sediment yield estimation

Reconstruction of sediment yield from lake sediment records is conceptually simple, but requires knowledge of a range of parameters including sediment density, trap efficiency, basin and reservoir size and time period over which deposition takes place (Verstraeten and Poesen, 2000; 2002). Estimation of these parameters may introduce errors and it may be necessary to show the possible range of sediment yield estimates due to differences in measurement and interpolation techniques (Evans and Church, 2000). In this section, differences in SSY estimates (Table 4.5) based on the different interpolation techniques and dBD values for the pit-based surveys are described.

To be able to perform an integrated data analysis based on the two different approaches (pit- and bathymetry- based), the results of the two methods for the Grashito and Maidelle reservoirs, which were surveyed based on the two techniques, were evaluated. Results show that SSY was about 30 and 23 t ha^{-1} y^{-1} (Grashito reservoir) and 24 and 21 t ha^{-1} y^{-1} (Maidelle reservoir) based on pit-based and bathymetric survey, respectively. This shows that the results of the two approaches are "consistent" with roughly 15% difference. In spite of their smaller magnitude, the differences mean, however, that caution is necessary when data from different sources and data collection based on different methods are integrated in any analysis.

Sediment yield estimation requires interpolation of point-sediment depth data to the whole reservoir area. In this study, Thiessen polygon, IDW, and average pit-depth-based estimation of sediment yield were tested (for the pit-based approach). The results of the three methods show that the average method tends to give slightly higher sediment yields, while the IDW gives lower values in relation to the Thiessen polygon method (Table 4.5). In general, sediment deposition tends to decrease with increasing distance from the embankment of the dam, and considering average pit-depth may overestimate sediment yield. On the other hand, the IDW method assumes a linear decrease in pit depth moving towards the inflow, which may not be necessarily true. The Thiessen polygon method, therefore, appears to be appropriate, as it partitions the reservoir area based on the "influence" of the respective pit depth.

To be able to compare results from different sources, sediment volume may need to be converted to mass using dBD data. The results presented in this study for all 11 reservoirs were based on mean dBD of 6 reservoirs. To assess disparity, sediment yield estimates using dBD values obtained for each of the 6 reservoirs are presented in Table 4.5. The sediment yield estimates based on the respective dBD values (SSY_{dBD}, Table 4.5) are close to those based on the average dBD values of the 6 reservoirs (SSY, Table 4.5). This may be attributed to the homogeneity of the sediments deposited in the reservoirs, which is also shown by the lower range of dBD value (160 kg m^{-3}).

The results of the bathymetric survey are based on the elevation differences of the reservoirs'-beds between two periods. In this case, the original capacity curves of reservoirs were compared with those computed during the survey. The existing capacity of the reservoirs is defined based on water surface level using datum benchmark or reservoir staff gauges. Since the studied reservoirs did not have staff gauges to monitor their water surface level, it was necessary to run leveling from the existing benchmarks which were mostly located far away from the dams. In some cases, it was very difficult to find the exact location of benchmarks without the assistances of the experts who conducted the original survey. Any slight error in the water level due to errors in benchmark location can lead to large errors in the final SSY values. During the field survey, for example, there were difficulties in exactly locating the benchmarks for the Teghane and Grashito reservoirs.

Table 4.5: Sediment deposition in reservoirs based on different interpolation methods and dBD values (for the pit-based survey) in Tigray, N. Ethiopia

Site name	**SSY_{IDW} ($t\ ha^{-1}y^{-1}$)**	**SSY_{AVG} ($t\ ha^{-1}y^{-1}$)**	**SSY_{dBD} ($t\ ha^{-1}y^{-1}$)**	**SSY ($t\ ha^{-1}y^{-1}$)**
Adiakor	2.4	6.0	5.0	5.0
Gerebsegen	9.6	14.8	11.4	11.7
Gindae	10.9	18.2	20.5	19.5
Grashito	20.0	36.0	31.6	30.2
Maidelle	18.2	29.0	21.8	23.6
Majae	6.9	10.3	6.8	6.8

SSY_{IDW} = SSY based on IDW interpolation; SSY_{AVG} = SSY based on average sediment thickness of sediment pits; SSY_{dBD} = SSY calculated using dBD (values in Table 4.2).
SSY = SSY based on TE values considering D = 0.1; dBD of 1260 t m^{-3} and Thiessen polygon interpolation method.

The original area-capacity data acquired from the Bureau of water resources were compared with the ones acquired from bathymetric survey of this study to estimate sediment deposition rate. The original area-capacity data were produced during design period of the dams and before actual construction of the dam embankment. It is, in some cases, common that some earth material could be removed during dam construction, which is not reflected in the original area-capacity curves. This may affect sediment volume estimation depending upon the volume of material removed after the original capacity curves were established. However, the overall sediment volume estimation may not be affected significantly as the burrowed earth material removed from one position of the reservoirs has been redistributed onto another portion to be used for compaction (Gebremedhin personal com.).

In general, SSY estimates are based on calculated and extrapolated values as indicated above, which may affect the absolute values of sediment yield. Careful calculation of the associated parameters and pursuing consistent procedures could minimize errors and give better SSY estimations.

4.5.2 Sediment yield and its relation with catchment area

Empirical models that relate annual sediment delivery with environmental attributes of catchments such as drainage area, terrain, LUC, lithology and climate are used to predict sediment yield (Walling, 1983; Hadley et al., 1985; Verstraeten et al., 2003). Catchment area is one of the most commonly used catchment attributes for predicting area-specific sediment yield (Lahlou, 1988). Catchment area could be considered as one of the terrain attributes that may easily be determined if maps of appropriate scale are available. Basin area is mostly estimated routinely when planning micro-dams, since this is one of the requirements to determine the volume of runoff and capacity of the reservoirs. Possibilities for predicting SSY based on catchment area or improving its capacity based on easily available data are therefore essential, especially for data-scarce regions in which the application of process-based models may not be feasible. There is however a need to evaluate the relationship between catchment area and SSY for local conditions before attempting to adopt empirical relationships established in other environmental settings (De Boer and Crosby, 1996; Schiefer et al., 2001).

Figure 4.5 shows the relationship between both SSY and SY and catchment area (A) of the studied sites. The A-SY trend (equation 4.5) shows that, as catchment area increases, the corresponding SSY also increases:

$$\log SSY = 0.61A^{0.27} \qquad R^2 = 0.26;\ n = 11;\ p = 0.1 \tag{4.5}$$

$$\log SY = 2.71A^{0.18} \qquad R^2 = 0.72;\ n = 11;\ p < 0.005 \tag{4.6}$$

Equation 4.5 (Figure 4.5a) controverts the conventional SSY and basin area relationship, which indicates a decline in sediment yield with increase in basin area (e.g., Walling, 1983; Verstraeten and Poesen, 2001a). The conventional model of SSY and basin area assumes that SSY decreases with increasing drainage area as a result of gentler hillslope gradients, sediment storage within the basin, and a decreasing percentage of basin area contributing sediment to the stream (e.g., Walling, 1983; Ritter et al., 1995; De Boer and Crosby, 1996).

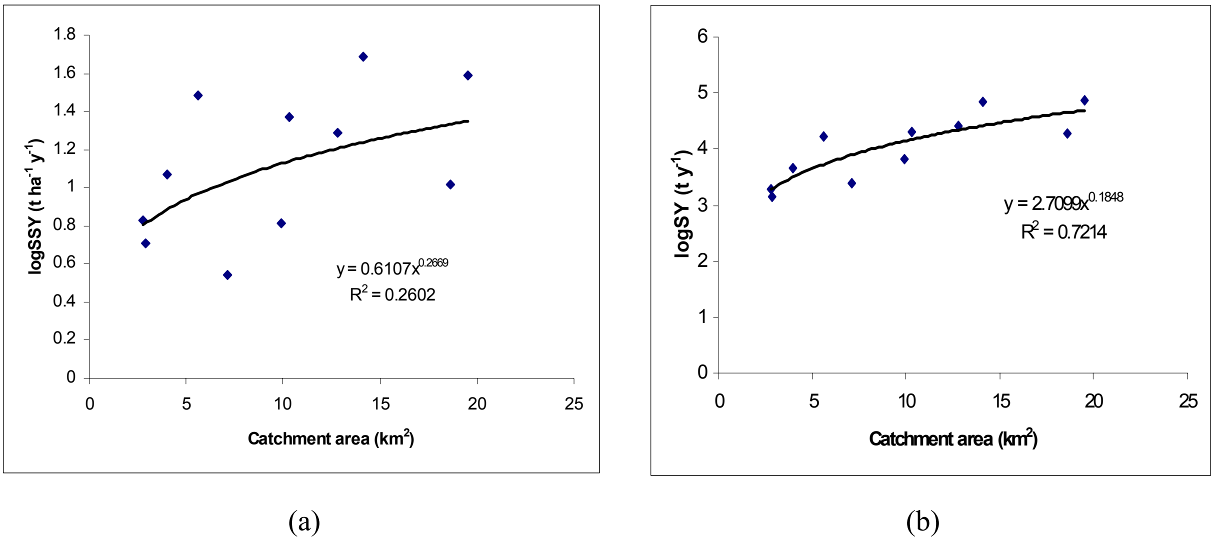


Figure 4.5: Relationship between SSY and SY with catchment area for selected sites in Tigray, N. Ethiopia

Several studies, however, reported that sediment yield could increase with basin size depending on terrain, erosion processes, and other unique characteristics of catchments (e.g., Kasai et al., 2001; Schiefer et al., 2001; Krishnaswamy et al., 2001). Walling and Webb (1996) showed that a positive relationship between SSY and catchment area is possible when the main sediment source is from channels (channel banks, channel bed and intermediate valley sides) in which case sediment delivery ratio (SDR) is above 1.0, and SDR and catchment area also take on a positive relationship. Sediment yield in headwater areas characterized by resistant rocks and good vegetation cover could be much lower than in downstream areas developed on softer, more erodible rocks, and in such circumstances SSY would increase downstream (Walling and Webb, 1996). Differences in the size of the catchments involved and their resulting diversified terrain attributes, erosion processes and local terrain could therefore govern the relationships between SSY and catchment area to be unique for different areas and not necessarily universal (Schiefer et al., 2001).

The above attributes are also observed for the study areas in which sediment remobilization by gullies is high, terrain shows pronounced differences and, in general, erodibility and the proportion of poor surface cover increase downstream. Most of the larger catchments in this study have high terrain and efficient catchment connectivity through gullies, which facilitate erosion and sediment delivery. Most of the floodplains, which have been formed through a long history of deposition, are becoming sediment sources rather than sinks, contributing to the accelerated rate of sediment deposition in reservoirs. On the other hand, the smaller catchments have generally low terrain and poor catchment connectivity, resulting in low net sediment export to reservoirs. These processes ultimately lead to an increase in SSY with increase in basin size. Analysis of the global SSY data presented by Lawrence and Dickinson (1995) also shows a direct relationship between SSY and basin area in different countries of Africa such as Kenya, Algeria, Lesotho and Zimbabwe, similar to the situation found in this study.

Nyssen et al. (2003) presented an SSY-catchment area relationship based on data from central and northern Ethiopian highlands as shown in Figure 4.6. Nyssen et al. (2003) further suggested that in conditions where measurement of suspended and bedload sediment is not possible, a rough estimation of SSY for an “average” Ethiopian catchment could be derived based on the equation presented in Figure 4.6. However, the data obtained for representative sites in the Highlands of northern Ethiopia based on 11 surveyed reservoirs show that SSY is inversely related to catchment area as opposed to the observations reported by Nyssen et al. (2003).

The difference between the data presented in Figure 4.5a and that in Figure 4.6 could be mainly attributed to differences in catchment size as most of the data in the former are derived from catchments of less than 20 km^2, while the data in Figure 4.6 are acquired from areas of extremely different sizes and environments. The integrated presentation of data from very different scales and sources may require stratification into different catchment sizes or agro-ecological conditions which would then result in a different relationship than originally sought (e.g., Lu and Higgitt, 1999). The visible existence of two clusters in terms of catchment size below and above roughly 100 km^2 in the data presented by Nyssen et al. (2003, Figure 4.6) also indicates that even stratification of the data using that “cut-off” boundary might result in a different relationship. Nyssen et al. (2003) also indicated the necessity of refining the model they have established for the highlands of Ethiopia (Figure 4.6), by including more data possibly grouped by agro-ecological regions. The data presented in Figure 4.6 were also collected during different periods (ranging from 1973 to 2001) with a possibility that the observed change in sediment yield with basin scale could be due to artifacts resulting from integration of data for different periods with different precipitation and runoff characteristics (De Boer and Crosby, 1996).

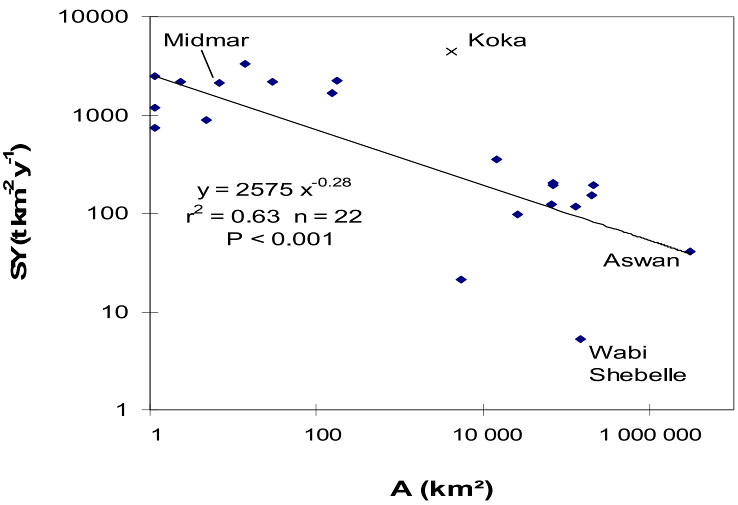


Figure 4.6: Relationship between SSY and basin A for different catchments draining the Ethiopian highlands (Source: Nyssen et al., 2003)

Waythomas and Williams (1988), Wasson (1994) and De Boer and Crosby (1996) suggested that relating annual sediment yield (SY) with catchment area and evaluating the exponent could provide an insight into the effect of basin scale on sediment transfer. By establishing a power relationship between SY and A, and noting the exponent, the effect of basin scale on SSY can be evaluated. An exponent with a value less than 1 indicates that drainage area increases faster than sediment yield, resulting in a downstream decrease of SSY (De Boer and Crosby, 1996). Based on this argument and referring to the SY- A relationship shown in equation 4.6 (Figure 4.5b) with an exponent value of 1.67, it may be concluded that annual sediment yield increases faster than drainage area, so that SSY increases downstream in the highlands of northern Ethiopia for the scale of catchments considered in this study.

Generally, the above SSY and A relationship and the possible explaining factors demonstrate that unless scale and environmental conditions, which may dictate erosion-deposition processes and their spatial distribution are considered, generalized use of the $SSY = A^{-b}$ power relationship may not necessarily hold to all environments and scales. This means that direct application of relationships established between SSY and A to predict SSYs of basins in different locations with different environmental factors could be misleading. In their discussion related to SSY-basin area relationship, De Boer and Crosby (1996) underlined the difficulty of extrapolating conclusions drawn at one specific scale to other scales without prior testing. Verstraeten and Poesen (2001a) and Lawrence et al. (2004) also show the difficulty of transferring SSY and A relations in one region to other regions if the sizes of catchments for which SSY and A relationships established are very different.

4.6 Conclusion

The reservoir surveys results in this study show that mean annual sediment yield in the reservoirs studied ranges from 3 – 49 t ha^{-1} y^{-1} with a mean SSY of about 19 t ha^{-1} y^{-1}. The sediment yield estimates show that most of the reservoirs have lost their dead storage capacity faster than their design life. Most of the reservoirs have lost 100% of their dead storage capacity in less than 25% of their anticipated life time. Only Teghane and Korir reservoirs lost relatively minimum live and dead storage capacities compared to the others.

If we use the sediment deposition data as proxy to assess the rate of soil loss from the catchments, it is possible to see that 5 of the 11 catchments studied have a soil loss rate above the maximum tolerable 18 t ha^{-1} y^{-1}. Such evidences indicate the magnitude of soil loss and its associated off-site effect on the water storage potential of reservoirs constructed for supplemental irrigation and livestock watering.

Quantification of the rate siltation is necessary to apply targeted management intervention to reduce catchment erosion and its off-site impacts. The results of this study could help to assess which reservoirs require urgent attention relative to the others and plan appropriate management interventions. Accordingly, reservoirs located in the Adigudom region require prior attention compared to the others.

In addition to their benefit for quantifying the rates of sediment yield for management plans, one important contribution of the surveys conducted in this study will be that the data can serve as crucial benchmarks against which future reservoir surveys can be compared for the monitoring of siltation problem in the region.

The relationship between SSY and catchment area shows a positive direction in contrast to the “universal” SSY- A relationship. This may be attributed to the co-existence of high terrain, poor surface cover and erodible lithology as well as gully erosion. Gully erosion of floodplains in some of the studied catchments which led sediment sinks to act as sediment sources, provide high sediment yield potential with decreased likelihood of sediment deposition. Sediment remobilization and erosion of floodplains supplemented by erosive water from higher elevations also increases SSY downstream. The increase in SSY with basin size observed in this study confirms that direct application of empirical relationships between SSY and basin area established for different locations with different erosion processes and environmental variables could mislead SSY estimation and result in ineffective policy recommendations.

5 ANALYSES OF FACTORS DETERMINING SEDIMENT YIELD VARIABILITY

5.1 Introduction

In Ethiopia, accelerated siltation of reservoirs, that are intended to provide irrigation water, has resulted in the loss of both the intended services from the dams and a large amount of money spent on their construction. At the same time, the on-site effect of erosion, which results in the loss of nutrient-rich top soil and hence reduced crop yields, is chronic in the country (e.g., FAO, 1986; Hurni, 1993).

In order to tackle the on- and off-site threats of erosion, there is a need for improved catchment-based erosion control and sediment management strategies (Boardman, 1998; Millward and Mersey, 2001; Walling et al., 2001). In order to prescribe problem-oriented cause treatment-based management intervention to tackle siltation, knowledge of the factors determining erosion-siltation processes is necessary. Knowledge of cause-effect relationships and their spatial patterns are also essential to plan appropriate sites for future water harvesting schemes and design necessary management precautions (Lawrence et al., 2004).

Despite the fact that reservoir siltation, caused by catchment erosion, is believed to be an important factor for the rapid storage loss of reservoirs in Ethiopia, there are no detailed studies conducted to understand the determinant factors of sediment yield variability on a catchment scale. There is therefore a need to understand the role of catchment attributes on sediment yield in reservoirs to understand the linkages between soil erosion processes on hillslopes and sediment yield in catchment outlets. To achieve this, quantitative data related to reservoir sediment deposition and catchment environmental attributes are needed.

A combination of bottom-sediment analysis and catchment monitoring provides a powerful conceptual and methodological framework for improved understanding of drainage basin sediment dynamics (Foster, 1995; Foster and Walling, 1994). Sediment deposition in reservoirs is a net reflection of catchment erosion and deposition processes, which are controlled by terrain, soils, surface cover, drainage network, and rainfall-related environmental attributes (Renard and Foster, 1983; Walling, 1994). Spatial variability in the environmental attributes of catchments may therefore reflect the spatial variability in sediment yield (Hadley et al., 1985; Verstraeten and Poesen, 2001a; Phippen and Wohl, 2003). Integrated analysis of reservoir sediment yield data with respective environmental attributes of reservoir catchments could facilitate understanding of the dominant factors governing sediment yield variability and identify cause-effect relationships at the catchment scale (Dearing and Foster, 1993; Phippen and Wohl, 2003).

This study evaluates the major determinant factors of reservoir sedimentation in a mountainous dryland environment of Northern Ethiopia. Information related to the amount and rate of sediment deposition in reservoirs were acquired for 11 sites. Corresponding catchment attribute data derived from different sources were then integrated with the results of the sediment yield data to evaluate the determinant factors of sediment yield variability. Understanding the significance of the different factors in accelerating erosion and sedimentation could enable prioritization of possible areas of management intervention, mainly targeted to addressing the major causative factors. The relationships between sediment yield and basin attributes could also serve as a means of predicting sediment yield of similar catchments in similar environments.

5.2 Study area and site characteristics

5.2.1 Site selection

In order to account for the role of terrain, LUC and management, and soil characteristics on erosion-siltation processes, 25 sites were visited in June 2002 and characterized in terms of different environmental variables. Out of the 25 sites visited, 11 sites which were assumed to be representative of the catchments of the reservoirs constructed in the region were selected for this study. Figure 5.1 shows the spatial distribution of the 11 study sites.

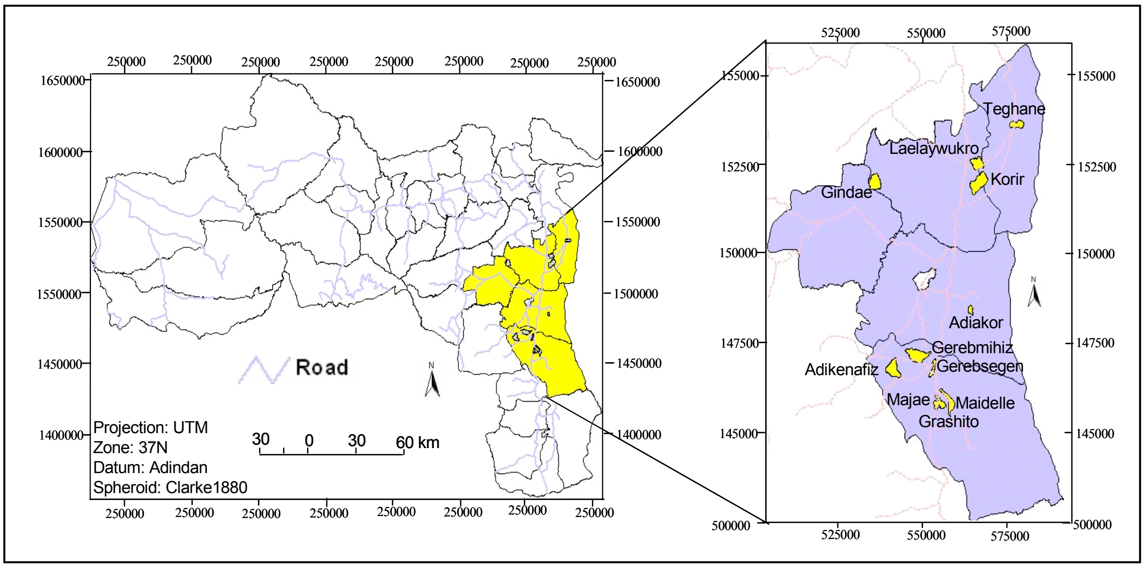


Figure 5.1: Spatial distribution of study sites in Tigray, N. Ethiopia

5.3 Materials and methods

After appropriate sites were selected, three main approaches were employed to estimate sediment yield and identify major determinant factors. First, quantitative sediment yield estimates were acquired; second, quantitative data on environmental attributes of catchments were collected; and finally, statistical methods were employed to analyze the relationship between catchment attributes and sediment yield in reservoirs. Figure 5.2 shows the details of the data collection, processing and analysis steps followed in this study. A brief description of the procedures is given below.

5.3.1 Data on sediment yield to reservoirs

Quantitative reservoir sediment deposition data related to annual and area-specific sediment yield were acquired for the 11 sites selected for this study based on the methods and procedures described in Chapter 4.

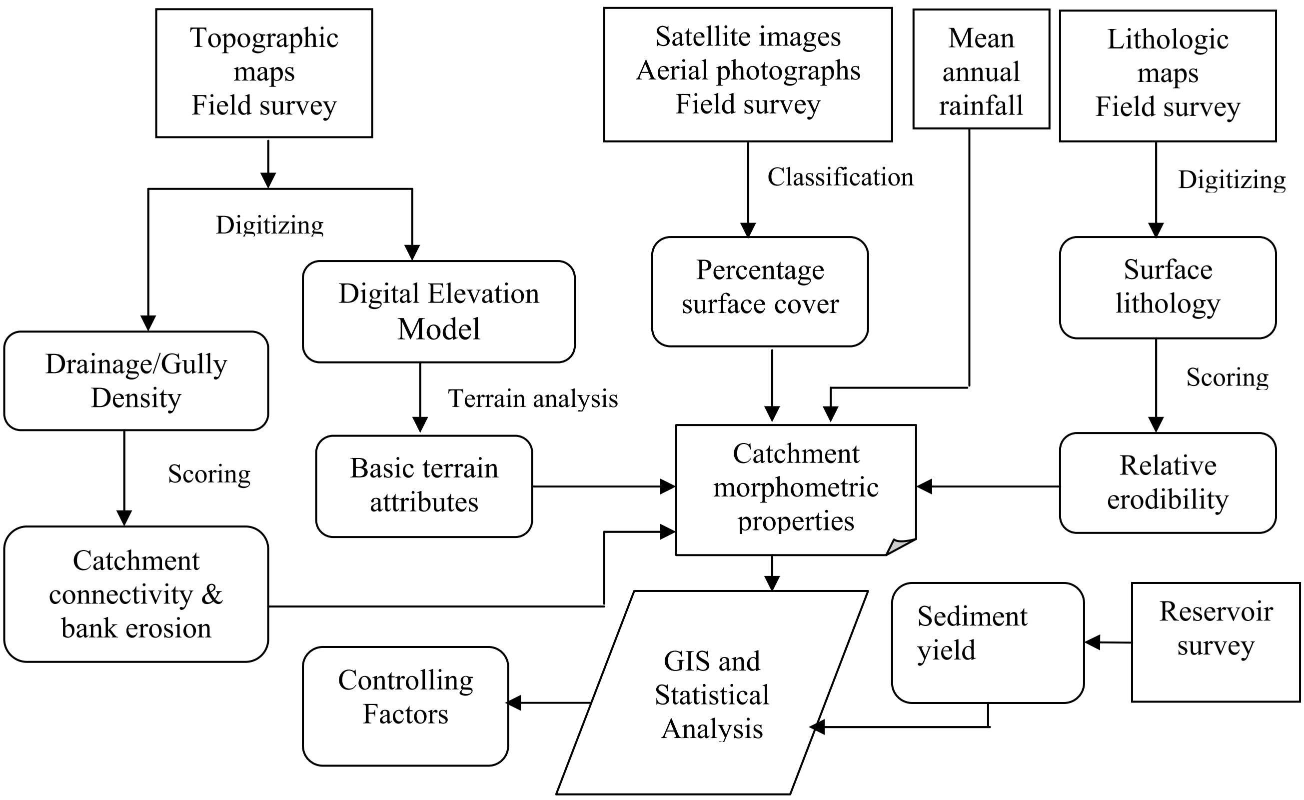


Figure 5.2: Procedures employed to extract information on catchment attributes and analyze controlling factors of reservoir siltation in northern Ethiopia

5.3.2 Morphometric properties of catchments

In order to assess the relationship between sediment yield in reservoirs and their respective catchment attributes, quantitative data related to major basin attributes that may influence catchment erosion-reservoir siltation processes were collected. Satellite images, aerial photographs, topographic maps and field survey were employed to acquire the data (Figure 5.2). Some of the key terrain attributes collected for this study and their possible role in erosion processes are described in Table 5.1.

To derive terrain-related parameters, topographic maps of 1:50,000 scale were acquired from the Ethiopian Mapping Authority (Ethiopian Mapping Authority, 1996). Contours, streams and spot heights were digitized from the topographic maps, and the TOPOGRID tool of ARC/INFO (Hutchinson, 1989) was used to construct digital elevation models (DEM) of 10-m cell size. Major topographic attributes such as slope, height difference, relief ratio, and hypsometric integral were then derived based on the

DEMs and methods described in Table 5.1. Catchment boundaries were defined using DEMs employing the CatchmentSIM program (Ryan and Boyd, 2003).

Land-use and -cover (LUC) maps of the catchments were derived from 15-m resolution ASTER images (near infrared bands) acquired for November/December 2001. Field surveys, supported by topographic maps, aerial photographs and GPS were used to collect training areas for the LUC classification. With the help of the training areas, the maximum likelihood algorithm of supervised classification in IDRISI was employed to derive LUC types for each catchment. The LUC maps were resampled to 10-m resolution to conform to the cell sizes of the DEMs.

In an environment where detailed soil data are not available, surface lithology could serve as a proxy to estimate erodibility potential (e.g., Evans, 1997; Fargas et al., 1997; Bull et al., 2003). Catchments with a larger proportion of shale/marl and limestone lithology are considered to be more sensitive to erosion than catchments dominantly covered with sandstone or metavolcanics (e.g., Fargas et al., 1997). Geomorphologic maps (Coltorti et al., undated and Russo et al., 1996) supported by field surveys were used to characterize catchments in terms of lithologic erodibility. The proportion of catchments covered with more sensitive lithology was estimated by digitizing the available maps.

Besides the above basic environmental variables of the catchments, data on gullies, which are prominent features in the region and substantially affect erosion-siltation processes, was also collected. Since it was difficult to acquire quantitative information on gullies and their status at a catchment scale, expert-based rankings were used to drive semi-qualitative data related to the severity of gully erosion and bank collapse. Three experts (the first author and two senior Hydrogeology students of Mekelle University), were involved in ranking the catchments for gully erosion-related processes. Each person assessed the status of gully erosion individually based on a transect-based survey. The number of transects range between 2 to 4 depending on the size and shape of catchments. During the survey, information related to the distribution of gullies (especially in relation to reservoirs) and their status (mainly related to qualitative dimension, disturbance by livestock, presence or not of cultivation up to the very edge of gullies and degree of bank collapse) were collected and evidence photos taken. Each expert then assigned ranks to each catchment based on the field observations. In order to derive discrete values which can be used in statistical analysis, the gully-erosion and bank collapse-related ranks of each expert were standardized using (Voogd, 1983; Eastman, 2001):

$$SBCR = \sum_{i}^{n} \left(\frac{R_i - n}{N - n} \right) / n * 100 \qquad (5.1)$$

where *SBCR* = standardized bank collapse and gully erosion; R_i = the actual rank given to each catchment by each expert, *N* = the maximum possible rank (11), *n* = the minimum possible rank (1), and *I* = the expert number (1-3). The result was multiplied by 100 to express it between 1 and 100.

Finally, mean annual rainfall data were acquired from the closest rainfall station of each catchment. As most rainfall stations are located in relatively large towns, and since rainfall data are not available for small towns, some of the catchments share the same amount of rainfall of a nearby station.

Table 5.1: Major catchment characteristics and their relation to erosion processes

Terrain attributes	Definition/description	Example reference
Catchment area	Proxy to discharge	Kirkby, 1988
Height difference (HD)	Runoff potential, erosive power *(HD =* $MaxE$ *,* $MinE$ *)*	Verstraeten & Poesen, 2001a
Slope	Flow velocity and momentum of runoff	Zevenbergen and Thorne, 1987; Moore et al., 1991
Hypsometric integral (HI)	Distribution of elevation within catchment $(HI = \frac{MeanE - MinE}{MaxE - MinE})$	Willgoose & Hancock, 1998; Awasthi et al., 2002; Bishop et al., 2002;
Relief ratio (RR)	Intensity of erosion process $(RR = \frac{MaxE - MinE}{L})$	Strahler, 1964; Verstraeten & Poesen, 2001a
Surface ruggedness (R)	Index of basin ruggedness $(R = H_b * A^{-0.5})$	Church and Mark, 1980
Main stream slope (SS)	Rate of change of elevation with respect to distance, surface runoff velocity $(SS = \frac{HD}{DL})$	Gordon et al. ,1992
Drainage length (DL)	Sediment transport potential *(DL = sum of length of all stream/gully length)*	Verstraeten & Poesen, 2001a
Drainage density (DD)	Balance between erosive forces and surface resistance, degree of dissection of terrain $(DD = \frac{DL}{A})$	Berger & Entekhabi, 2001; Sarangi et al., 2003; Tucker at al., 2001
(Catchment shape) circularity ratio (CI) and elongation ratio (ER)	Speed of sediment delivery, deposition potential $(CI = \frac{A}{ACp}, \quad ER = \frac{D_c}{L})$	Gordon et al., 1992; Sarangi et al., 2003

$MeanE$, $MaxE$, $MinE$ = mean, maximum, and minimum elevations of the catchment (m); L = horizontal distance between the outlet of a catchment and the most remote point on the water divide (m); H_b = height difference (basin relief) and A = basin planimetric area; HD = height difference (m); DL = drainage length (km); ACp = area of a circle having a perimeter equal to the perimeter of the catchment under consideration (m^2); D_C = diameter of a circle with the same area as the catchment area (m) and L = maximum length of the watershed (m).

5.3.3 Statistical analysis

Different statistical analyses including Pearson's correlation, principal component analysis (PCA) and multiple regression were performed to assess the relationship between sedimentation of reservoirs and their respective catchment characteristics. Correlation analysis was used to investigate to what extent the amount of sediment in reservoirs is related with each of the environmental variables identified for each reservoir catchment. PCA was used to reduce data redundancy by placing similar entities in proximity in ordination space where the relationships among sampling entities can be evaluated by the entities' relative positions on the newly defined gradients (Chappell et al., 1996; McGariaal et al., 2000). PCA helps to define the patterns of variation in SSY in terms of catchment attribute with multicollinearity kept to the minimum (Phippen and Wohl, 2003). In addition, multiple regression was run on those variables with high factorial loadings of each component to evaluate the effect of a combination of factors on sediment yield.

5.4 Results

5.4.1 Sediment deposition in reservoirs

The amount and rate of sediment deposition in the 11 surveyed reservoirs is presented in Table 4.3 (Chapter 4). The annual rate of sediment yield (SSY) into reservoirs ranges roughly between 3 and 49 t ha^{-1} y^{-1} with a mean SSY value of 19 t ha^{-1} y^{-1}. More detailed discussion of the observed siltation of reservoirs is provided in Chapter 4. Since the range in the values of SSY spans over 15 orders of magnitude (Table 4.3) showing high variance, a logarithmic transformation was applied to the SSY data before analysis.

5.4.2 Morphometric properties of catchments

Table 5.2 shows the major catchment attributes derived from the sources and methods discussed in section 5.2. Several catchment attributes were derived and/or calculated. The factors that play a significant role in erosion/deposition processes are presented in Table 5.2. These attributes are then related with sediment yield data to evaluate the role of each factor on SSY variability.

5.4.3 Correlation analysis

Table 5.3 shows the correlation between SSY estimates reported in Table 4.3 (Chapter 4) with the respective reservoir catchment attributes shown in Table 5.2. The correlation matrix in Table 5.3 shows that height difference (*HD*), ruggedness number (*R*), lithology (*EL*) and gully-related erosion (*SBCR*) have a significant correlation with SSY. All are significant at 0.05 level except gully erosion/bank collapse which is significant at 0.01 level.

The *HD* is positively and significantly correlated with logSSY (r = 0.64). This means that catchments with high absolute elevation differences would have higher SSYs, because with rapid changes in elevation, the runoff and potential energy available to detach and transport soil particles could be higher. The *R* is also significantly correlated with logSSY (r = 0.60), because removal of water and sediment from the channel and watershed surface increases as the slope of a catchment varies (Sarangi et al., 2003).

The *EL* shows a good positive correlation with logSSY (r = 0.68). This indicates that catchments dominantly covered with erodible shale and marl lithology would have a higher SSY than others, since such lithologic surfaces are more prone to soil detachment and transport. Similar observations are reported in different studies (e.g., Lahlou, 1988; Woodward, 1995; Fargas et al., 1997). On the other hand, catchments dominantly covered with less erodible and more resistant rocks such as sandstone and metavolcanics (e.g., Laelaywukro, Teghane, Korir catchments) show low siltation risk partly because of the limited supply of fine sediments. Phippen and Wohl (2003) also found similar results in their study in the Rio Puerco Watershed, New Mexico.

The significant correlation between logSSY and the *SBCR* (r = 0.92) may be due to the fact that a dense network of gullies (Figure 5.3) provides efficient connectivity throughout the catchment to deliver sediment to downslope positions (Poesen et al., 2003). Gullies are also major sources of sediment in most of the catchments due to bank collapse and through remobilization of sediment deposited in floodplains. Similar findings are reported in different studies (e.g., Ownes and Slaymaker, 1993; Wasson, 1994; Trimble, 1995; Walling et al., 1998). Similar to the observations in other regions (e.g., Trimble and Mendel, 1995; Lloyd et al., 1998;

Boardman et al., 2003), livestock disturbances of gully floors and banks as well as trampling of areas nearby reservoirs (Figure 5.3c) worsen the process of gully erosion in most of the study sites. The presence of eroding and collapsing gullies downslope could also be associated with a high intensity of erosion processes and thus increased potential of sediment delivery to channels and reservoirs.

(a) (b) (c)

Figure 5.3: Examples of (a) gully erosion of floodplains, (b) gully bank collapse, and (c) livestock disturbance of gully banks and floors in Tigray, N. Ethiopia. These processes correspond with the catchments of the three reservoirs with the highest sediment yield (Table 4.3, Chapter 4)

The correlation matrix in Table 5.3 shows that SSY is negatively correlated with circularity ratio (*RC*) which is opposite to that normally expected. The possible reason could be that *RC* is correlated with some catchment variables in an opposite direction to the correlation between those same attributes and SSY. For instance, *RC* is negatively correlated with height difference, gully erosion and erodibility related factors while these same factors are positively and significantly correlated with SSY.

Table 5.2: Basic morphometric properties of studied catchments in Tigray, N. Ethiopia

Site No.	Site name	A	MEE	HD	RR	HI	MES	SS	R	DL	DD
1	Adiakor	2.9	2393.5	81.0	0.03	0.53	2.9	17.9	48.5	6.6	2.4
2	Adikenafiz	14.0	2377.8	664.7	0.09	0.39	10.7	77.2	177.0	34.3	2.4
3	Gerebmihiz	19.5	2253.7	659.3	0.07	0.23	7.9	72.4	149.0	46.0	2.4
4	Gerebsegen	4.0	2125.0	122.4	0.02	0.37	1.6	19.2	61.0	7.9	2.0
5	Gindae	12.8	2143.9	487.5	0.10	0.40	8.4	82.6	136.2	15.4	1.2
6	Grashito	5.6	2117.8	295.9	0.05	0.44	5.6	34.4	125.5	10.8	1.9
7	Korir	18.6	2232.7	607.0	0.08	0.38	11.0	104.4	140.7	36.1	1.9
8	Laelaywukro	9.9	2240.0	551.8	0.08	0.43	16.4	79.0	175.2	37.1	3.7
9	Maidelle	10.3	2177.0	527.0	0.05	0.34	5.3	50.0	164.3	4.8	0.5
10	Majae	2.8	2138.4	170.6	0.04	0.48	5.4	45.3	101.4	3.3	1.2
11	Teghane	7.0	2790.5	177.8	0.03	0.40	8.8	30.8	66.9	10.9	1.5

Table 5.2: Continued

Site name	RF	SBCR	ER	RC	EL	DENSE	CULT	NGL	BUSH	TBARE
Adiakor	568	16.7	1.9	0.81	81	2.5	72.0	9	13	81
Adikenafiz	668	93.0	4.2	0.33	93	9.0	60.4	13	17	73
Gerebmihiz	668	96.7	5.0	0.68	90	7.5	61.4	14	16	75
Gerebsegen	550	40.0	2.3	0.53	98	0.5	81.0	5	11	86
Gindae	690	70.0	4.0	0.88	88	9.5	39.0	15	33	54
Grashito	658	80.0	2.7	0.66	97	1.2	85.0	9	4	94
Korir	685	60.0	4.9	0.80	41	18.5	38.2	9	31	47
Laelaywukro	677	36.7	3.6	0.79	25	15.5	33.0	13	37	46
Maidelle	658	43.0	3.6	0.53	95	2.5	77.0	11	8	88
Majae	634	10.0	1.9	0.79	83	0.5	66.0	17	8	83
Teghane	559	3.0	3.0	0.35	20	10.5	46.0	12	17	58

A = catchment area (km^2), MEE = mean elevation (m), HD = height difference (m), RR = relief ratio (-), HI = hypsometric integral (-); MES = mean slope (degrees), SS = main stream slope (m km^{-1}); R =surface ruggedness (-);DL = drainage length (km), DD = drainage density (km km^{-2}); RF= mean annual precipitation (mm); SBCR =standardize bank collapse and gully erosion (-); ER = elongation ratio (-), RC= circularity ratio (-); EL = proportion of erodible lithology (%);DENSE = proportion of dense cover (enclosures) (%); CULT =proportion of cultivated/bare land (%); NGL = proportion of non-restricted grazing land (%); BUSH =proportion of bush/shrub cover (%); TBARE = proportion of total bare/crop land (%).

Table 5.3: Correlation between catchment attributes and SSY for the 11 reservoirs. Note that SSY was transformed to logSSY

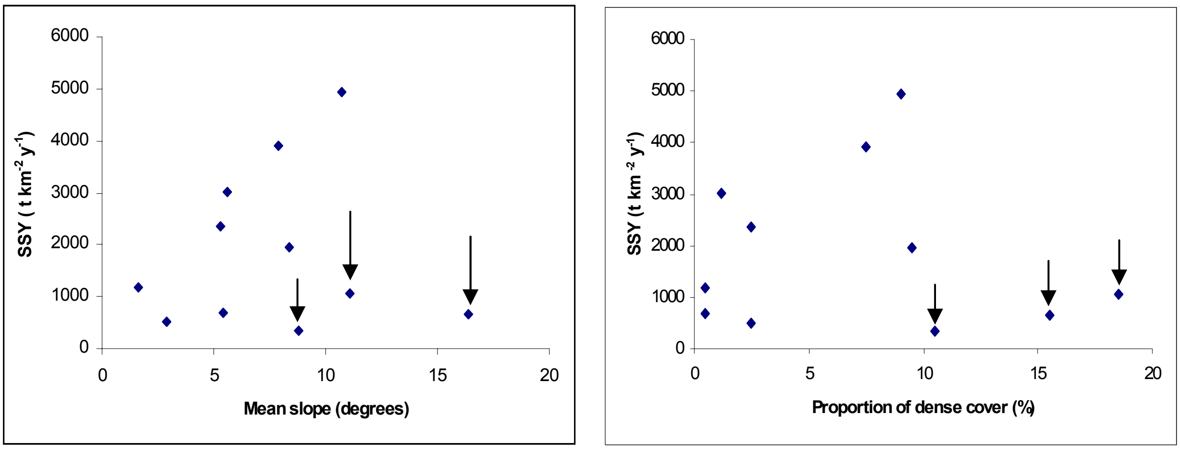
	A	MEE	HD	RR	HI	MES	SS	R	DL	DD	RF	SBCR	ER	RC	EL
A	1.00														
MEE	-0.03	1.00													
HD	0.91**	-0.18	1.00												
RR	0.76*	-0.22	0.85**	1.00											
HI	-0.73*	0.07	-0.62*	-0.28	1.00										
MES	0.55	0.19	0.67*	0.71*	-0.13	1.00									
SS	0.85**	-0.19	0.88**	0.91**	-0.38	0.76*	1.00								
R	0.68*	-0.32	0.92**	0.81**	-0.44	0.68*	0.78**	1.00							
DL	0.84**	0.03	0.80**	0.68*	-0.54	0.72*	0.76**	0.62*	1.00						
DD	0.13	0.10	0.20	0.23	0.09	0.55	0.20	0.17	0.63*	1.00					
RF	0.68	-0.46	0.84**	0.88**	-0.30	0.61	0.86**	0.90**	0.57	0.06	1.00				
SBCR	0.69*	-0.38	0.73	0.66*	-0.58	0.21	0.53	0.64*	0.62*	0.17	0.65	1.00			
ER	0.99*	-0.01	0.93**	0.78*	-0.73*	0.60*	0.86**	0.72*	0.82**	0.13	0.70	0.69*	1.00		
RC	0.02	-0.54	-0.01	0.25	0.29	0.07	0.28	0.01	0.05	0.12	0.36	-0.04	-0.03	1.00	
EL	0.24	-0.40	0.27	0.17	-0.47	-0.36	-0.01	0.22	0.16	-0.08	0.05	0.75*	0.22	-0.26	1.00
DENSE	0.68*	0.29	0.60*	0.65*	-0.20	0.86*	0.79**	0.45	0.72*	0.43	0.46	0.16	0.70*	0.12	-0.43
CULT	-0.49	-0.31	-0.42	0.62*	0.03	-0.82**	-0.70*	-0.31	-0.54	-0.34	-0.40	0.05	-0.51	-0.28	0.53
NRG	0.22	0.05	0.32	0.47	-0.04	0.41	0.41	0.41	0.19	-0.10	0.50	0.04	0.22	0.20	-0.09
BUSH	0.52	0.06	0.51	0.70*	-0.08	0.79**	0.74*	0.40	0.60*	0.48	0.45	0.12	0.55	0.38	-0.37
TBARE	-0.48	-0.32	-0.39	-0.56	0.03	-0.79**	-0.67*	-0.25	-0.53	-0.38	-0.33	0.06	-0.50	-0.26	0.55
SY	0.75*	-0.05	0.74*	0.57	-0.69*	0.23	0.49	0.59*	0.67*	0.15	0.50	0.84**	0.72*	-0.27	0.72*
logSSY	0.52	-0.45	0.64*	0.50	-0.57	0.01	0.35	0.63*	0.36	-0.09	0.57	0.92**	0.53	0.19	0.68*

Table 5.3: continued

	DENSE	CULT	NGL	BUSH	TBARE	SY	logSSY
DENSE	1.00						
CULT	-0.90**	1.00					
NGL	0.16	-0.42	1.00				
BUSH	0.87**	-0.92**	0.24	1.00			
TBARE	-0.93**	0.98**	-0.25	-0.94**	1.00		
SY	0.17	-0.02	0.40	0.03	0.03	1.00	
logSSY	-0.13	0.31	0.16	-0.19	0.34	0.81**	1.00

*Symbols are explained in Table 5.2. ** sig. at 0.01; * sig. at 0.05.*

Table 5.3 shows that mean slope is poorly correlated with SSY. This may be because the role of some factors is masked by others. It is observed that steep slope areas are correlated with dense surface cover and resistant lithology while gentle slope areas have generally poor surface cover and erodible lithology as a result of which the separate effects of slope becomes less clear (Rustomji and Prosser, 2001). For instance, Laelaywukro, Korir and Teghane sites have complex terrain with a high potential for erosion and sediment yield. But, these catchments are characterized by less erodible lithology and relatively good surface cover, which reduce the severity of erosion and sediment contribution (Figure 5.4). This could be due to the fact that the effect of terrain on erosion/sediment yield is masked by its correlation with cover types and surface lithology (Table 5.3). When the effect of some variables is masked by others, it may be necessary to stratify sites based on some terrain attributes or exclude the “outliers” from analysis (e.g., Lu and Higgitt, 1999).



(a) (b)

Figure 5.4: Scatter plot showing the positions of Laelaywukro and Korir catchments when SSY is plotted against selected attributes: even if their slope is high, their SSY is not because of their relatively dense surface cover and less erodible lithology.

The relationship between SSY and some catchment attributes improved when correlation was performed after excluding the above mentioned catchments from the analysis (Table 5.4). This shows the effect of natural complexity and spatial heterogeneity on environmental modelling (Jakeman et al., 1999) and demonstrates the necessity of stratification when heterogeneous catchment attributes with complex interactions affect erosion/sediment yield and complicate the analysis. However, it should be noted that the improved correlation between SSY and some of the "terrain" based factors is at the expense of "decreased" correlation with the LUC related factors.

Table 5.4: Partial correlation between selected catchment attributes and SSY after stratification (exclusion of two sites). Note that the 4 factors that were significant at 0.05 (n =11) became highly significant at 0.01 (n = 8)

Terrain factor	**Correlation (n = 11)[1]**	**Correlation (n = 8)[2]**	**Terrain factor**	**Correlation (n = 9)[3]**
Catchment area	0.53	0.80	Height difference	0.85
Mean slope	0.01	0.73	Surface ruggedness	0.87
Drainage length	0.53	0.71	Erodible lithology	0.69
Elongation ratio	0.84	0.78	Gully erosion	0.93

[1]Not significant at either 0.05 or 0.01; [2]Significant at 0.05. [3]Significant at 0.01.

5.4.4 Principal component analysis (PCA)

PCA was applied for 20 catchment attributes to reduce the dimensionality of data into a few components and to assess whether there were gradients in the data structure that could better explain SSY variability. The first four components account for about 88% of the variability in the dataset. Table 5.5 shows the factor loadings (eigenvector values) of the respective terrain attributes of the four components.

From Table 5.5, it is possible to see that the eigenvalues associated with the first two principal component axes contain over 71% of the variance in the dataset while the other two contain about 17%. The first two components also have high eigenvector values for each variable while the last two have low eigenvector values. The last two PCs do not contain clear, identifiable and logical dimension, implying potential PCs with relatively little merit for further analysis (Burley et al., 1996). Step-wise regression performed between the 4 PCs and logSSY using the probability F for entry (0.05) and removal (0.1) also selected the first two components only ($R^2 = 0.92$, $p < 0.001$). The correlation between logSSY and the factors forming PC3 and PC4 (drainage density) also seem to be more "noisy" as their relationship with logSSY is opposite to what is expected (Table 5.3), which may be because these factors are negatively correlated with the other terrain factors which are positively correlated with sediment yield. As a result, the first two PCs, which explain most of the variability in the dataset and show meaningful relationship with sediment yield, were considered for further analysis.

The high eigenvector coefficients for the first PC (bold values) are all positive, except hypsometric integral, suggesting that the dependent variables covary together and are relatively equitable (Burley et al., 1996). The set of variables with high loadings of PC1 are mainly composed of terrain, elongation ratio, catchment area, gully erosion, drainage length and rainfall, explaining about 50% of the variability. Since catchment area, elongation ratio and drainage length are significantly correlated with most of the terrain-related variables (Table 5.3), the major elements of the PC1 can be considered as terrain-, gully-erosion-, and precipitation-related factors.

Table 5.5: Eigenvalues, percentages of variation (%Var) explained and eigenvectors of variables for each component evaluated by PCA. Bold italic values indicate highest eigenvector score for a given variable

Parameter PCA	Variable	PC1	PC2	PC3	PC4
Eigenvalue		10.3	4.0	2.0	1.3
% Var		51	20	10	7
Eigenvector	Height difference	**.928**	.270	0.076	0.164
	Elongation ratio	**.903**	.350	-0.080	0.046
	Catchment area	**.896**	.323	-0.059	0.032
	Standardized gully erosion	**.889**	-.213	0.170	-0.103
	Ruggedness number	**.805**	.181	0.214	0.308
	Hypsometric integral	-.780	.128	0.345	0.086
	Drainage length	.775	.484	0.008	-0.260
	Mean annual precipitation	.729	.213	0.484	0.370
	Main stream slope	.725	.544	0.277	0.229
	Relief ratio	.724	.434	0.351	0.292
	Proportion of total bare land	-.171	**-.957**	-0.034	-0.045
	Proportion of cultivable land	-.186	**-.944**	-0.057	-0.183
	Proportion of dense cover	.401	**.891**	-0.039	-0.050
	Proportion of erodible lithology	.197	**-.889**	0.264	0.069
	Proportion of bush/shrub cover	.259	**.870**	0.274	-0.030
	Mean slope	.431	.815	0.048	0.122
	Circularity ratio	-.117	.221	0.864	-0.022
	Mean elevation	-.252	.424	-0.800	0.033
	Proportion of open grazing land	.233	.239	0.065	0.767
	Drainage density	.141	.469	0.163	-0.623

The eigenvector coefficients for PC2 have positive and negative values showing that the factors do not always covary together. For instance, a high proportion of erodible lithology is negatively associated with dense surface cover, an increasing proportion of bare/cultivable land is negatively associated with bush/shrub cover, and a high slope angle is inversely related to erodible lithology. The set of variables in PC2 (which explain about 20% of the variability) are mainly composed of LUC-, erodible lithology- and mean slope-related attributes. Mean slope is significantly and positively correlated with bush/dense cover and negatively correlated with cultivated/bare land and lithologic erodibility (Table 5.3). As a result, PC2 can be considered as an LUC- and lithology-related axis.

Generally, the results of the PCA show that topography, gully erosion, precipitation, LUC types and surface lithology play a significant role in explaining the variability of sediment yield in the studied catchments. The model that best explains the variability in SSY based on the two principal components is:

$$\log SSY = 0.314PC_1 - 0.191PC_2 + 1.129$$
$$R^2 = 0.92; n = 11; P < 0.005 \quad (5.2)$$

where PC_1 and PC_2 = factor loadings of the significant principal components.

According to Equation 6, sediment yield is more sensitive to changes in terrain- and gully-related factors than to changes in LUC and lithology. This shows that the relative contribution of PC1 to sediment yield variability is higher than that of PC2. This is also revealed in the correlation matrix shown in Table 5.3 in which the terrain-related factors such as *HD* and *R* and *SBCR* are significantly correlated with logSSY, whereas none of the LUC-related factors are significantly correlated with logSSY.

The two significant principal components were plotted against each other as shown in Figure 5.5 to visually evaluate the spatial arrangement of variables in the PC space. Observation of the data pattern within the PC1 and PC2 spaces shows the catchments that are grouped close together based on their unique catchment attributes. By observing the catchments that are “nearby” or “far apart”, it may be possible to find the reasons behind those spatial arrangements. This may indirectly help to assess the major reasons for SSY variability between catchments.

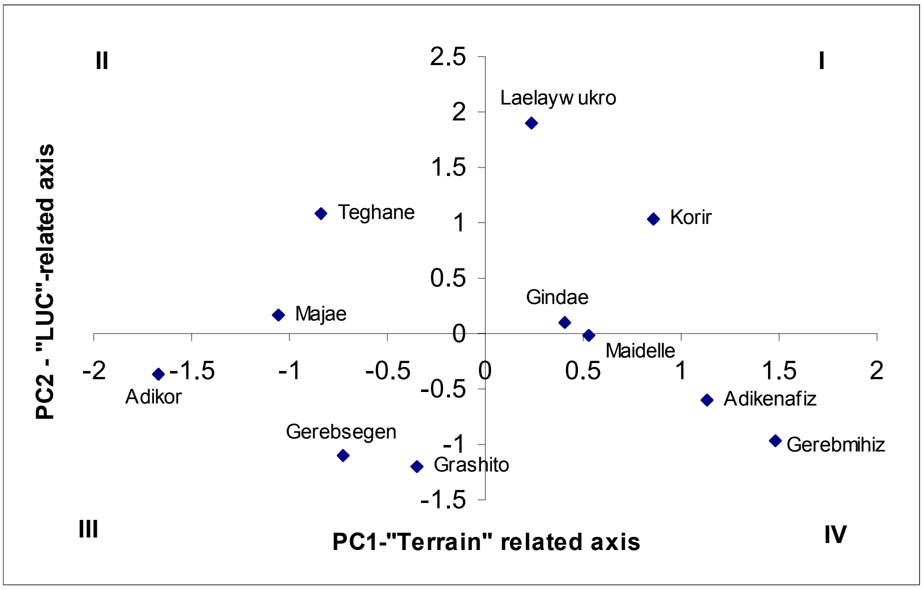


Figure 5.5: Distribution of observed SSY within PC spaces

Catchments located within the first and fourth Quadrant are based on the highest factor loading of PC1 (height difference). The distinction between the sites in these two spaces is due to the fact that those on the upper end of the first Quadrant have attribute such as low erodibility and good bush/shrub cover in addition to rugged terrain. Catchments located at the upper end of the top Quadrants I and II (Korir, Laelaywukro and Teghane) are at a relatively proximate space mainly due to their similarity in the proportion of resistant lithology. All those near or in the lower Quadrants (III and IV) have generally similar shale- and marl- dominated lithology. The spatial arrangement of the sites in the left side of Quadrant III (Adiakor), those in Quadrant II (Majae and Teghane) and the site at the top of Quadrant I (Laelaywukro) is mainly due to low gully erosion. Adiakor sits on the end of Quadrant III (PC1) due to its hypsometric integral, which is higher than for the other sites. This may be because there are steep slopes closer to the reservoir. Laelaywukro is located at the extreme end of Quadrant I (PC2) due to its relatively high proportion of bush cover, high mean slope and low proportion of cultivated land compared to the others. Gerebsegen and Grashito took proximity space because they have relatively similar shape, mainly elongation ratio.

PC1 is more important in distinctly separating the different catchments than PC2, because there is more heterogeneity in the attributes of catchments with respect to the PC1 factors (e.g., height difference) than in those of PC2 (e.g., proportion of bare land). For instance, reclassification of the variables in Figure 5.5 based on their distinct groupings would lead to Figure 5.6. Figure 5.6a separates sites plotted within Quadrants I and IV from the others, based on height difference. Figure 5.6b differentiates sites plotted in Quadrant I plus Teghane in Quadrant II from the others, mainly based on surface cover. Comparison of the Figures (a-d) shows that catchments in the former are better segregated than in the latter, signifying the dominant role of factors forming PC1 compared to those forming PC2 (equation 5.3) in determining SSY variability of catchments. The Figures also demonstrate the benefits of PCA in placing sites with similar entities in proximity enabling the assessment of the relationships between entities based on their relative positions.

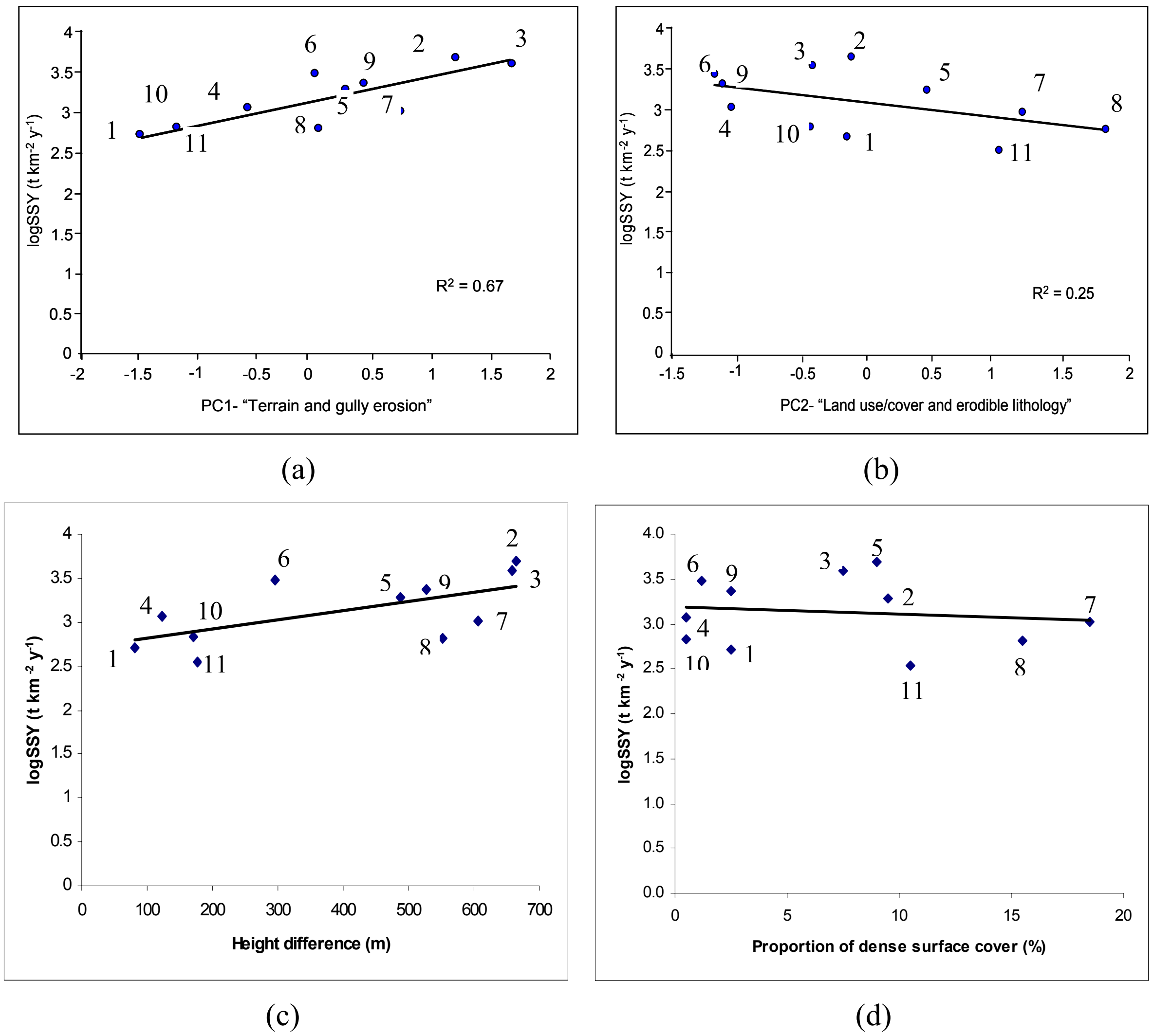


Figure 5.6: Catchments grouped based on (a) PC1, (b) PC2, and example component scores (c) *HD*, (d) *DENSE* (1= Adiakor, 2= Adikenafiz, 3=Gerebmihiz, 4=Gerebsegen, 5=Gindae, 6=Grashito, 7=Korir, 8=Laelaywukro, 9=Maidelle, 10=Majae, 11=Teghane)

5.4.5 Multiple regression analysis

Correlation analysis cannot show the effect of a combination of independent variables on a dependent variable and cannot be used for predictive purposes. The PCA enables assessment of the role of a combination of factors, but the results cannot be directly used for prediction purposes, since the real values of catchment attributes are lost during PC transformation. Regression analysis was, therefore, used to assess the cause-effect relationships between a combination of catchment attributes and corresponding SSYs. Before applying multiple regression, it was necessary to keep the number of explanatory variables (20) lower than the number of cases (11) to avoid the problem of inflated R^2 (Phippen and Wohl, 2003). It was also necessary to minimize the effect of autocorrelation of environmental factors on multiple regression analysis (e.g., (Phippen and Wohl, 2003). The PCA made it possible to reduce the dimensionality of the data and to address the problem of multicollinearity.

From the four PCs (Table 5.5), four catchment attributes with high eigenvector values were selected and the actual values of these factors were entered into a regression. Table 5.6 shows that over 80% of the variability in sediment yield can be explained by terrain- (e.g., height difference) and LUC- (e.g., cultivated land) related factors, with minor contributions from the other variables of PC3 and PC4 (which are not significantly correlated with logSSY, Table 5.6). A similar level of significance was achieved (over 80%) when height difference and dense cover or total bare land were entered into the regression (not shown here). When the gully/bank-erosion-related factor and LUC types (bare/cultivated or dense/bush cover) were entered into the regression analysis, the variability explained increases to over 95% (Table 5.6) with the surface cover related factors also being significant. The interesting output of the regression models is, therefore, that the contribution of LUC- types to SSY variability is revealed, which was not the case with the correlation, as none of the LUC-related parameters were significantly correlated with logSSY.

Table 5.6: Multiple regression coefficients estimated by each unstandardized statistical model for the 11 sites. SSY is transformed to logSSY

Model	Independent variable	β estimate	Standard error	P-value	Pearson's r
(R^2 = 0.84)	Height difference	0.0016	0.000	0.000	0.64*
P = 0.002	Cultivated land	0.015	0.003	0.012	0.30
	Drainage density	-0.024	0.08	0.77[1]	-0.09
	Circularity ratio	0.030	0.35	0.94[1]	-0.19
	Constant	-0.38			
(R^2 = 0.95	Gully/bank erosion	0.011	0.001	0.000	0.92**
P < 0.001	Cultivated land	0.004	0.002	0.09	0.30
	Drainage density[1]	-0.08	0.043	0.11[2]	-0.09
	Circularity ratio[1]	-0.16	0.186	0.43[2]	-0.19
	Constant	0.60			

*** Significant at 0.01. *Significant at 0.05.*
[1]Exclusion of these non-significant variables does not reduce the significant level of the other factors.

A step-wise regression technique was also run using 18 factors to identify the factors that explain most of the variation in observed sediment yield, while the multicollinearity between independent variables was kept to the minimum. Only 18 variables were used because two factors, mean elevation and circularity ratio, which are negatively correlated with most of the terrain attributes that are positively and significantly correlated with logSSY, were excluded. The best predictive equation that can be constructed to estimate area-specific sediment yield in reservoirs is:

$$\log SSY = 0.007SBCR + 0.003EL + 0.002R - 0.007BUSH + 2.33$$
$$R^2 = 0.95; sig. < 0.05 \tag{5.3}$$

where *SSY* = area-specific sediment yield (t km^{-2} y^{-1}), *SBCR* = standardized bank collapse/gully erosion (-), *EL* = proportion of erodible surface lithology such as shale and marl (%), *R* = surface ruggedness (-), *BUSH* = proportion of bush/shrub cover (%).

The model in equation 5.3 shows once again that terrain-, lithology-, gully- and LUC-related factors explain most of the variation in SSY, which is in agreement to the result of the PCA.

When we run regression after excluding gully erosion, the most significantly correlated variable with SSY, the following relationship could be established:

$$\log SSY = 0.0011HD + 0.009EL + 0.019$$
$$R^2 = 0.87, sig. < 0.001 \tag{5.4}$$

where *HD* = elevation difference (m) and *EL* = proportion of erodible lithology (%).

The general purpose of multiple regression analysis is to learn more about the relationship between several independent or predictor variables and a dependent variable. Once the relationships are established, the equations can be used to predict the status of a dependent variable in relation to the independent variables. The equations presented in Table 8 and equation 7 or 8, for example, can be used to predict the SSY of other similar catchments provided that basic catchment attribute data are available. However, since the size of the samples used in this study are small, detailed analysis for a larger number of sites will be required to establish a robust prediction model of annual sediment yield.

5.5 Discussion

Analyses of controlling factors of siltation based on sediment deposit in reservoirs and corresponding environmental attributes of catchments show that terrain, gully erosion, lithology, and surface cover play significant role.

In general, the presence of weak, easily detachable lithologic surface, eroding floodplain (good sediment supply from locations near to reservoirs) and pronounced terrain (high potential energy to detach, transport and deliver sediment) as well as poor surface cover (less friction and shear strength of materials) in the study areas accelerate the siltation sensitivity of the reservoirs. The intensive rainfall of short duration, which onsets after the long (around nine months) dry season also accelerates erosion, as it falls on open surfaces with minimum protection. Due to the co-existence of pronounced terrain, poor surface cover and easily erodibility lithology, the degree of surface dissection is higher and spectacular gullies are common phenomena.

Gully erosion may be considered as a very important factor playing double role: both supply and transport of sediment (Figure 5.3, 5.7). From the 11 catchments, 4 (with high SSY) have a high rate of bank collapse and gully erosion, whereas 3 (with low SSY) show very limited evidences of gully erosion. The rest (medium SSY) are in the intermediate position. More gullied catchments produced about double the SSY of less gullied catchments. A study in eastern Ethiopia by Shibru et al. (2003) also shows high contribution of gullies (about 25 t ha^{-1} y^{-1}) to soil loss. These evidences suggest that attention needs to be given to the rehabilitation/stabilization of gullies and their banks, and prevent their destabilization due to livestock trampling.

The location of reservoirs may also have an implication for the severity of siltation. It is common practice that water storage schemes are located at the confluences of two or more streams to collect runoff water. However, locating reservoir dams just below eroding and collapsing gullies (Fig. 5.3, 5.7) could lead to a higher risk of accelerated siltation. Three of the reservoirs with high SSY are, for instance, characterized by such spectacular gullies starting from the dams up to more than 2-3 km upslope. It may, therefore, be necessary to avoid locating reservoirs at the mouth of eroding and collapsing gullies or to apply relevant conservation and stabilization measures before building dams.

(a)

(b)

Figure 5.7: Reservoirs located just below such eroding and collapsing gullies show a higher probability of rapid siltation (a) Adikenafiz catchment and (b) Gerebmihiz catchment in Tigray, N. Ethiopia

A closer look at the environmental factors of the catchments shows that cultivated land is positively correlated with erodible lithology (Fig. 5.8a) and less erodible lithology is positively correlated with slope (Fig. 5.8b). In addition, gully erosion is positively correlated with height difference (Fig. 5.8c). Such interactions between the different factors favor both detachment and transport processes, ultimately increasing the potential siltation risk of the reservoirs downstream. In most instances, erosion and transport enhancing factors co-exist, which could increase potential soil loss and its downstream delivery

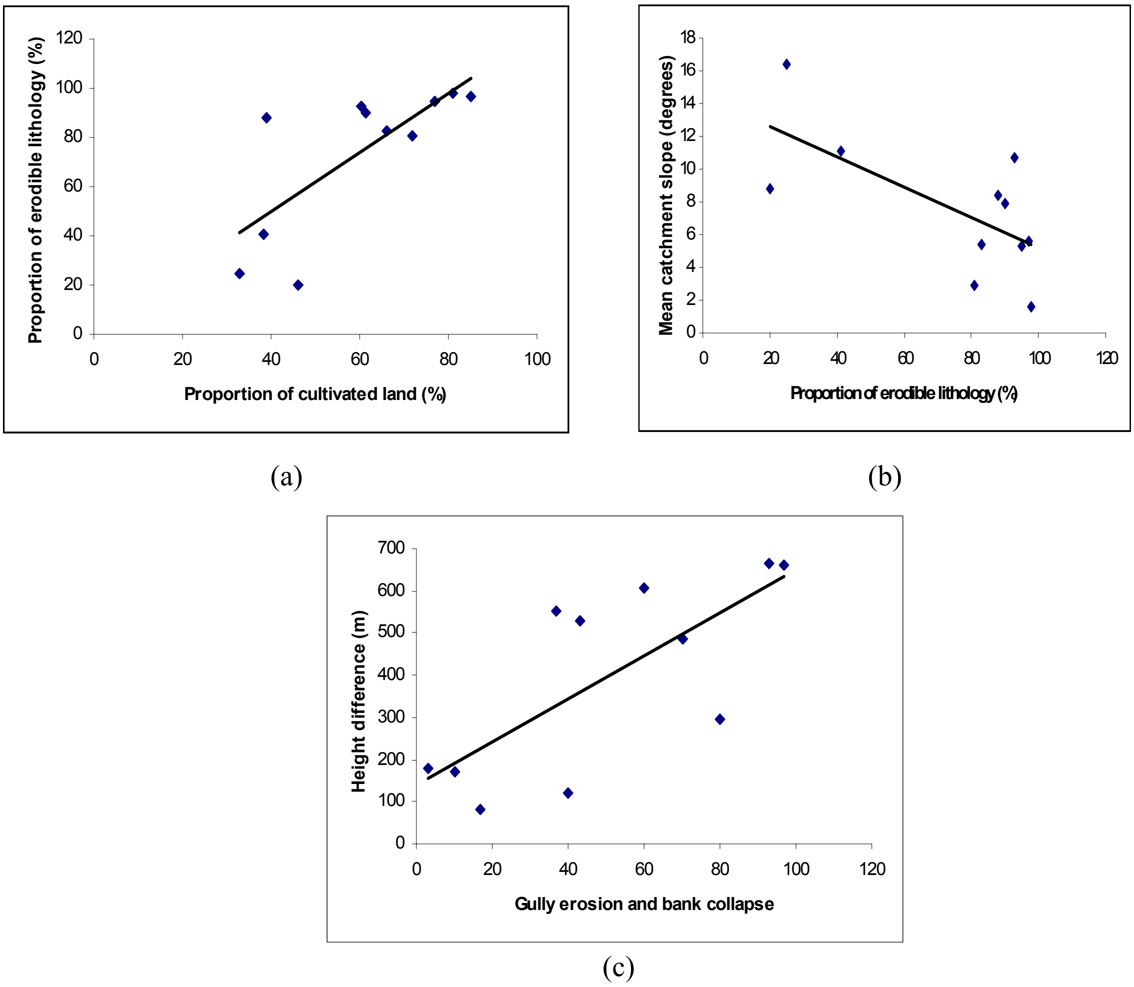


Figure 5.8: Interaction between natural and anthropogenic factors and their possible contribution to erosion and sedimentation in Tigray, N. Ethiopia

The correlation analyses results show that mean slope is poorly correlated with sediment yield. One main reason for this could be that the role of slope is masked by the effect of other factors. For instance, slope is negatively correlated with easily erodible lithology (Table 5.3), which is also observed in a study by Kirkby et al. (2003) and Mills (2003). On the other hand, slope is positively correlated with dense surface cover, which can retard detachment and transport of soil particles. It is also observed that most of the conservation and afforestation efforts are concentrated at the relatively steep slope and remote positions compared to the downslope positions. In addition, most of the steep slopes are located at the relatively remote parts of the catchments in relation to the reservoirs. This may influence their effect on the siltation rate, as the distribution of slopes in relation to the reservoirs is more important than a single lumped slope value (Verstraeten and Poesen, 2001a). The influence of slope is, therefore, neutralized by the combined effects of natural and human factors making its relation to sediment yield less very clear.

The rapid water storage loss of some of the reservoirs may be attributed to the absence of catchment management before and after dam construction. When water harvesting schemes are planned, there should be prior conservation of the upslope catchments to reduce rapid siltation (Morris and Fan, 1998). In the case of the Tigray region, there was a great rush to build as large a number of dams in as short a time as possible without prior detailed study of possible sedimentation problems and management options. The ambitious plan for constructing around 500 micro-dams in 10 years mainly focused on rapid preliminary surveys of possible locations. These problems played a significant role in the rapid failure of most of the water harvesting schemes (CoSaERT, 1999).

The benefits of proper catchment management and conservation to reduce reservoir siltation can be demonstrated by the example catchments shown in Fig. 5.9. Reservoirs where comparatively proper catchment management and conservation practices are in place before and after dam construction (e.g., Laelaywukro and Korir) show relatively low sediment deposition despite high terrain potential for erosion (Fig. 5.9). This demonstrates the necessity of employing proper catchment conservation in order to reduce rapid storage loss of the reservoirs and achieve the intended objective of improving food security. However, it has to be noted that the widespread conservation efforts undertaken in the region need to be properly maintained as there are several cases where terraces are broken, largely due to livestock trampling or runoff. This could have a serious implication on the effectiveness of the conservation measures and even may allow concentrated flow which could enhance erosion and the development of gullies downstream.

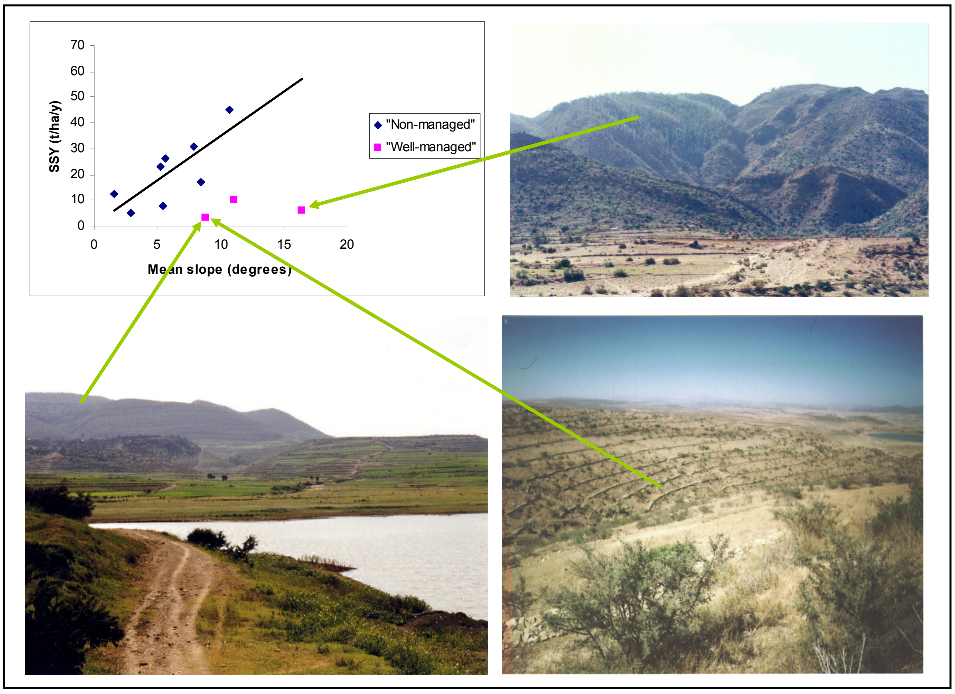


Figure 5.9: Role of good surface cover and management practices in reducing SSY in Tigray, N. Ethiopia. "Non-managed" refers to catchment with no enclosures (protected areas) and "well-managed" refers to catchments with protective surface cover such as enclosures and buses/shrubs. The bottom right photo shows dense stone terraces constructed to reduce soil erosion (Korir catchment)

Because only lumped attributes of catchments were used in this study, the spatial distribution of the factors responsible for siltation cannot be determined. However, the results in the analyses provide an insight into which of the terrain attributes land managers should focus on to tackle the rapid loss of storage capacity of the reservoirs. The terrain- and lithology-related factors may not be directly manipulated but can be modified through land management. Covering the upland non-cultivable areas with vegetation and conservation of gullies could reduce the speed of runoff flow and its erosive capacity, ultimately reducing the rate of siltation of reservoirs downstream (Figure 5.9).

5.6 Conclusion

Identification of the major causative factors that provoke erosion and accelerate siltation processes is necessary to guide and apply targeted management interventions. Against this background, different statistical analyses were performed to assess the role of different catchment attributes in the siltation of reservoirs.

The results show that pronounced terrain (high potential energy to detach, transport and deliver sediment), easily detachable lithologic surfaces, eroding floodplains (good sediment supply from locations near to reservoirs) and poor surface cover (less friction and shear strength of materials) in the studied catchments accelerate the siltation sensitivity of the reservoirs. The intensive rainfall of short duration, which onsets after the long dry season also accelerates erosion, as it falls on open surfaces with minimum protection. Due to the co-existence of pronounced terrain, poor surface cover and easily erodible lithology, the degree of surface dissection is high and spectacular gullies are common phenomena.

The fact that some of the catchments show lower SSY rates despite complex terrain highlights the importance and significance of proper site selection and catchment management practices in reducing erosion and sediment delivery. Management interventions targeted at protecting sensitive upslope areas, rehabilitating gullies, and preventing livestock from overgrazing areas around reservoirs and disturbing gully floors could retard the rate of soil loss and its associated off-site impact.

This study also demonstrates that erosion assessment techniques in environments such as those in Tigray should take into account the contribution of gully erosion and bank collapse. Since gullies play significant role in dictating sediment yield variability in the study sites, approaches that do not consider gully erosion may underestimate the soil erosion and siltation risk of reservoirs. The semi-qualitative expert-based techniques applied in this study to determine the severity of gully erosion gave encouraging results. Future work will, however, be needed focusing on detailed quantitative assessment of gullies and their spatial pattern

6 MODELLING LANDSCAPE SUSCEPTIBILITY TO EROSION AND POTENTIAL SEDIMENT SOURCE AREAS

6.1 Introduction

Soil erosion is the major form of land degradation, resulting in on-site nutrient loss and off-site sedimentation of water resources (e.g., Boardman, 1998; Morris and Fan, 1998; Lal, 1999). The off-site effects of erosion such as reservoir sedimentation and water resources pollution are usually more costly and severe than the on-site effects on land resources (Phillips, 1989). Tackling the off-site effects of soil erosion requires an understanding of the rates and spatial distribution of erosion and deposition processes as well as identification of the major controlling factors that enhance or retard these processes. The knowledge of "what are the factors?" may help to distinguish the potential causes and the associated reasons behind the respective causes. This may not be enough to design site-specific management, as the factors playing a major role in erosion-siltation may be widely distributed within catchments (Ferro et al., 1998). As all landscape positions are not equally sensitive to erosion, one important approach to tackling siltation could be to identify where the sources of most of the sediments are within the catchment (Dickinson and Collins, 1998). Identification of "hotspot" areas of erosion for appropriate management interventions to tackle the major causative factors at their specific locations is, therefore, imperative from an economic, management and sustainability point of view.

High-potential sources of sediment can vary across the landscape due to specific attributes and processes within different positions of the landscape. Sensitive areas can be identified by combining attributes that enhance susceptibility, which is a result of interaction of both natural terrain attributes and anthropogenic practices. Soil erosion models represent an efficient means of investigating the physical processes and mechanisms governing soil erosion rates and amounts (Boggs et al., 2001). Erosion models can be used as predictive tools for assessing soil loss, conservation planning, soil erosion inventories as well as for understanding erosion processes and their impacts (Nearing et al., 1994; Morgan, 1995). The major benefit of soil erosion models at the landscape scale is that they enable predicting erosion sensitive areas and identifying major sources of sediment (Jetten et al., 2003).

A wide range of models that differ in their data requirement for model calibration, application, complexity and processes considered are available for use in predicting sediment and pollutant transport (Merritt et al., 2003). Physically based spatially distributed soil erosion models can be used to quantitatively determine the amount of soil loss from catchments and also to identify critical sediment source areas (De Roo, 1998). The successful application of such models, however, depends on the availability and quality of data for calibration and validation (De Roo, 1998; Stefano et al., 1998; Takken et al., 1999). Such problems are more pronounced in developing regions where data availability is scarce, existing data are not easily accessible and data collected and stored are mostly in different formats. In addition, more complex models do not necessarily perform better for basin-scale management purposes, mainly because input errors can increase with increasing model complexity (Favis-Mortlock, 1998; Mitas and Mitasova, 1998a; Jetten et al., 2003; Merritt, et al., 2003). Empirical models are frequently used in preference to complex physically based models as they can be implemented in situations with limited data and parameter inputs, particularly as a first step in identifying sources of sediment (Merritt et al., 2003). However, such models cannot be directly applied to environments other than those for which they were developed, and extrapolation of results from larger-scale plot-level to small-scale catchment-level application is difficult (Dickinson and Collins, 1998). In addition, such models could be more site-specific and simplified to handle catchment dynamics, which makes their application to relatively large sites inappropriate. It is therefore necessary to identify models that are not very much simplified and under-represent the physical basis or not too complicated and very expensive to implement.

Currently, spatially distributed terrain-based models, which emphasize the effect of terrain shape and topographic complexity on erosion/deposition processes are in widespread use (Moore and Burch 1986; Moore et al., 1991; Desmet and Govers, 1996a; De Roo, 1998; Mitas and Mitasova, 1999, Van Oost, 1999). The central idea behind the theory of terrain-based models is that topography is the dominant control on the spatial variation of hydrological processes at the hillslope scale, and simple model formulation with topography being emphasized in some more detail may allow reproduction of the basic patterns of erosion and deposition in complex landscapes (Desmet and Govers, 1996a; Wilson and Gallant 2000; Mitasova et al., 2001). Terrain-based distributed models permit both the spatial heterogeneity of the catchment land use, soil properties and topography to be represented, and can therefore provide spatially distributed predictions of soil erosion for complex three-dimensional terrain (Mitasova et al., 1998a, b).

Recent advances in the development of GIS have promoted the application of terrain-based distributed soil erosion and sediment delivery models at the catchment scale (Moore et al., 1991; Maidment, 1996; De Roo, 1998). Linking erosion simulation models with GIS provides a powerful tool for land management, as it helps to model large catchments with a greater level of detail, the presentation of results in more user-friendly formats, greater power of data manipulation and the ability to provide a detailed description of catchment morphology through analysis of digital elevation models (DEMs) (Dickinson and Collins, 1998; De Roo, 1998; Mitas and Mitasova, 1998a). GIS technology also allows basin characteristics controlling sediment detachment, movement, and storage to be considered in a spatially explicit and varying manner (Harden, 1993).

A good model is one that can satisfy the requirements of reliability, universal applicability, ease of use with minimum data, comprehensiveness in terms of the factors and erosion processes included and the ability to take account of changes in land-use and management practices (Morgan, 1995). However, no single model can satisfy all these requirements or is the "best" for all applications (Grayson and Blöschl, 2000; Istanbulluoglu et al., 2002; Merritt et al., 2003). The choice of models may depend upon the purpose for which they are needed, the accuracy and validity of the model, resources available and the scale and detail of application. Models with an adequate physical basis but with optimum data requirement for calibration and validation would be preferable, mainly for developing and data-scarce regions (Fistikoglu and Harmancioglu, 2002). As there can be no single model that can satisfy all purposes, it may also be desirable to apply a combination of models and compare their results with measured data in the region under study.

This study aims to apply different terrain-based models in a GIS environment to (1) predict the rate of soil loss and sediment delivery potential of catchments and (2) assess the spatial patterns of erosion/deposition to identify critical source areas of sediment. Three terrain-based models, i.e., the Sediment Transport Capacity Index

(STCI) (Moore and Burch, 1986), the USLE2D (Desmet and Govers, 1996a), and the Unit Stream Power-based Erosion/Deposition (USPED) (Mitasova et al., 1997, 1999, 2001) were applied by integrating with rainfall erosivity, soil erodibility, land-use and land-cover (LUC) types and conservation practices. The models were applied in four catchments with different terrain characteristics. The result of models were compared with quantitative (^{137}Cs and soil profile) and semi-quantitative (field-based erosion sensitivity) data collected for the studied catchments. Soil loss rates predicted by the models were also compared with sediment accumulation in reservoirs to identify the model that best agrees with annual sediment deposition data.

6.2 Study area and methodology

6.2.1 Site selection

For this study, four representative catchments (Figure 6.1) were identified to implement the three erosion models. The sites were selected based on the sediment yield in reservoirs, incorporating those with high, medium, and low deposition rates. The reservoirs Adikenafiz and Gerebmihiz showed high sediment yield, Maidelle showed medium while Laelaywukro had a low sediment yield. Differences in basin characteristics such as terrain, lithology, LUC, and erosion intensity were also the basis of site selection.

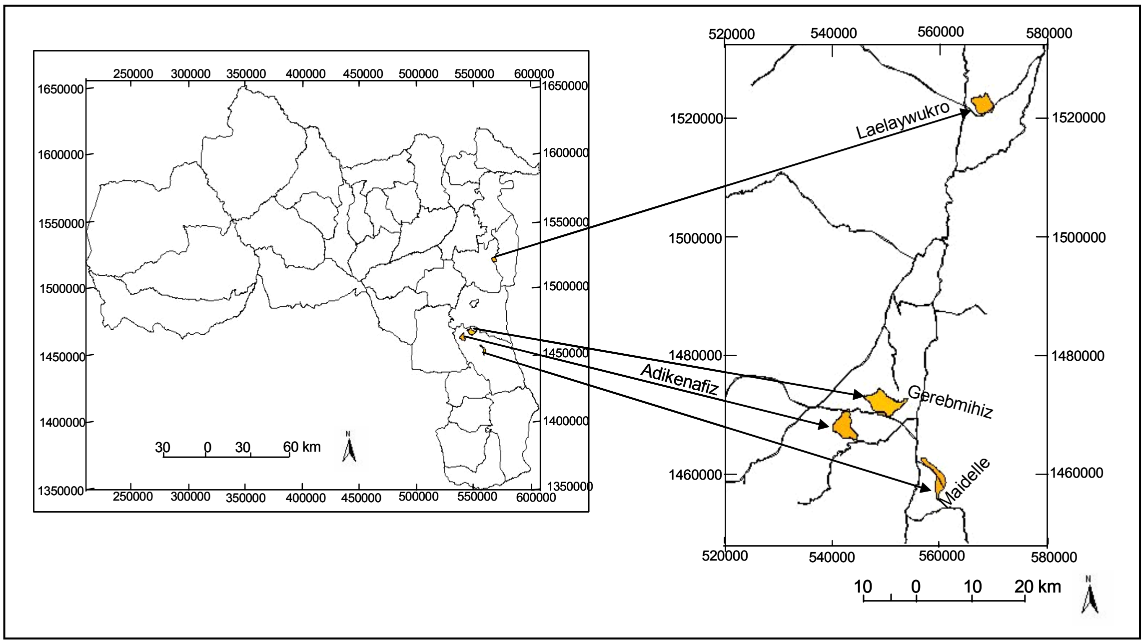


Figure 6.1: Spatial distribution of selected study sites in Tigray, N. Ethiopia

Generally, Laelaywukro followed by Adikenafiz and Gerebmihiz are the most complex catchments with pronounced terrain and curvature, whereas Maidelle has relatively simple terrain and an elongated shape. Maidelle, Gerebmihiz and Adikenafiz are characterized by highly erodible lithology, mostly shale and limestone, whereas Laelaywukro is dominantly covered with less erodible sandstone/metamorphic rocks. Maidelle has the poorest surface cover followed by Gerebmihiz and Adikenafiz, while Laelaywukro has a relatively good bush/shrub cover. Gerebmihiz and Adikenafiz are characterized by a dense network of collapsing gullies, mostly extending up to reservoirs; Maidelle and Laelaywukro have relatively less intensive gully erosion.

6.2.2 Materials and methods

Soil erosion is a function of natural and anthropogenic processes including rainfall, soil characteristics, terrain, LUC and conservation practices (Renard and Foster, 1983; Goldman, 1986):

$$E_r = f(C_l, S_{pr}, T_y, SS_c, H_a) \tag{6.1}$$

where E_r = erosion; C_l = climate; S_{pr} = soil properties; T_y = topography; SS_c = surface cover and management conditions; H_a = conservation and support practices.

The interaction of these processes determines the rate and magnitude of erosion as well as its temporal and spatial variability. Detailed information on the nature and distribution of these factors is required to assess the rate of soil loss and its spatial pattern. Figure 6.2 shows the procedures followed to estimate the rate of erosion and identify sediment source areas. Approaches followed to collect data on the status of the above factors, to model rates and patterns of soil loss as well as to evaluate model results are discussed in the following sections.

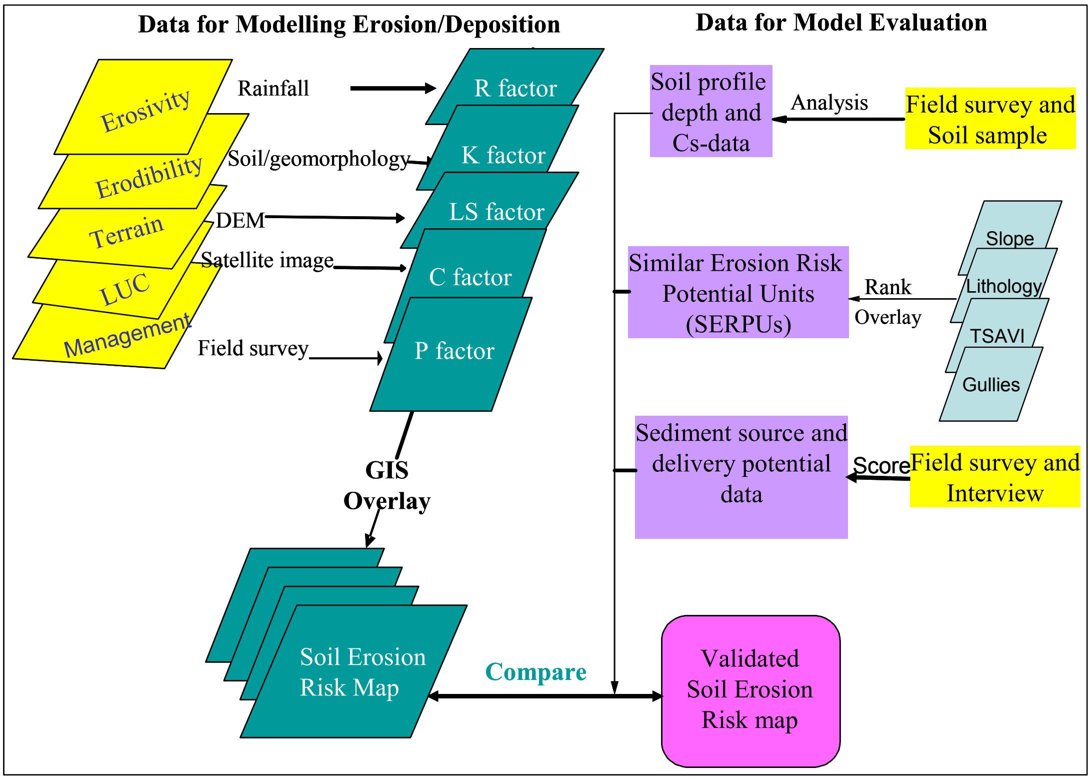


Figure 6.2: Schematic representations of major data sources, processing steps and output related to soil erosion risk assessment (Source: author)

6.3 Derivation of the major erosion parameters (factors)

6.3.1 Rainfall erosivity (R) factor

Soil loss is closely related to rainfall through the detaching power of raindrops striking the soil surface and the transportation power of runoff (Morgan, 1995). Rainfall intensity is generally considered to be the most important rainfall characteristic that is related to soil detachment and transport (Morgan, 1995). The R factor is defined as the product of kinetic energy and the maximum 30 minute intensity and shows the erosivity of rainfall events (Wischmeier and Smith, 1971). Theoretically, the kinetic energy (E in J) of the rainfall drop is given by the formula:

$$E = 0.5MV^2 \tag{6.2}$$

where M (kg) = mass and V (m s^{-1}) = velocity.

Measurements of kinetic energy and raindrop size are generally not readily available, and empirical relationships are established between rainfall intensity and kinetic energy as shown by (Wischmeier and Smith, 1958; Renard et al., 1997):

$$E = 11.9 + 8.73 \log_{10} I \tag{6.3}$$

where E = kinetic energy (Jm^{-2} mm^{-1}) and I = rainfall intensity (mm h^{-1}). Rainfall erosivity can then be evaluated based on the following formula (Renard et al., 1997):

$$R = \sum (EI_{30}) / N \tag{6.4}$$

where R = rainfall erosivity, E = total storm energy (J m^{-2} mm^{-1}), I_{30} = maximum intensity for 30 minutes of rainfall (mm), and N = period of observation (y).

Equation 6.4 cannot be directly applied in regions where rainfall intensity data are not available. It is also not possible to directly apply erosivity equations proposed in (Revised) Universal Soil Loss Equation (R)USLE (Wischmeier and Smith, 1978; Renard, et al. 1997) to other areas due to differences in rainfall characteristics.

For Ethiopia, Hurni (1985) established a relationship between mean annual rainfall and rainfall erosivity based on the analysis of monthly rainfall data of different stations. The R factor adopted for Ethiopian conditions by Hurni (1985), with the following form, was used in this study to estimate the erosivity value of catchments based on rainfall data of nearby stations (Table 6.1).

$$R = 5.5P - 47 \tag{6.5}$$

where R = annual rainfall erosivity (MJ mm ha^{-1} h^{-1} y^{-1}), and P = annual precipitation (mm) acquired over the last 35 years. The values of P = 599mm (Adikenafiz and Gerebmihiz), P = 673mm (Laelaywukro), and P = 576mm (Maidlle) were used in this study.

6.3.2 Soil erodibility (K) factor

The K factor is defined as the rate of soil loss per unit of R on a unit plot (Renard et al., 1997). The rate of soil loss depends on the relative easiness of the soil for detaching and transporting forces. Soil erodibility is mainly a function of texture, organic matter (OM) content, structure and permeability (Wischmeier et al., 1971). Texture and OM can be determined using laboratory measurements, whereas permeability and structure can be acquired from field observation and measurement. Once these data are available, the following equation can be used to derive the K factor (Renard et al., 1997):

$$100K = \left[2.1M^{1.14}\left(10^{-4}\right)\left(12 - OM\right) + 3.25(s-2) + 2.5(p-3)\right]/7.59 \qquad (6.6)$$

where K = erodibility factor, in t ha h (ha MJ mm)$^{-1}$; M = particle size parameter = (%silt + %sand)* 100 - %clay); OM = percent organic matter; s = soil structure code; p = permeability class. The division by 7.59 is to get values expressed in SI units of t ha (ha MJ mm)$^{-1}$ (Renard et al., 1997).

The above equation was used to derive the K value for 2 of the catchments (Gerebmihiz and Laelaywukro) for which soil data were available. Soil samples for texture and OM analysis were collected from soil pits located at different positions in the catchments, mainly considering terrain, LUC and lithologic attributes. During sampling, a soil profile description was carried out and information related to permeability and structure was obtained. The samples were collected from representative positions of the catchment, and erodibility values were extrapolated to the whole of the catchment based on terrain and lithology. For the Adikenafiz and Maidelle catchments, K factor values were estimated based on geomorphological units suggested by Feoli et al. (1995) and Machado et al. (1996a, b) as shown in Table 6.1.

6.3.3 Cover-management (C) factor

The C factor is defined as the ratio of soil loss from land with specific vegetation to the corresponding soil loss from continuous fallow (Wischmeier and Smith, 1978). In order to account for the influence of surface cover on erosion/deposition rates and spatial patterns, LUC maps of catchments were derived from ASTER satellite images of 15 m resolution acquired for November/December 2001. The images were resampled to 10 m cell size to conform cell sizes of other data. Based on training areas collected from field surveys, the maximum likelihood supervised classification algorithm in IDRISI (Eastman, 2001) was used to produce land cover maps. The accuracy of the classification was evaluated using an error matrix in IDRISI, which compares the classified image with training areas representing the same land cover features. The accuracy assessment was performed for selected parts of the catchments, which represented the whole of the catchment in terms of LUC properties. The classification produced an overall Kappa value of 0.78 to 0.86, indicating that pixels composing the test training sites were classified more than 78% - 86% better than would be expected from a chance assignment (Lillisand and Keiffer, 1994). The lower value is for the Laelaywukro catchment and was due to a shadowing effect of terrain, which influences the spectral reflectance values of pixels. Generally, the major cover types identified were dense cover, bushes/shrubs, non-restricted and restricted grazing areas, and cultivated fields.

Experimental studies since the USLE have suggested different values for different cover types and management practices (e.g., Wischmeier and Smith, 1978; Renard et al., 1997). It is, however, difficult to apply those values to other environmental settings. For this study, C factor values suggested by Hurni (1985) for different crop and surface cover types in Ethiopia were employed (Table 6.1).

6.3.4 Support practice (P) factor

The P factor gives the ratio between the soil loss expected for a certain soil conservation practice to that with up-and down-slope ploughing (Wischmeier and Smith, 1978). Specific cultivation practices affect erosion by modifying the flow pattern and direction of runoff and by reducing the amount of runoff (Renard and Foster, 1983). In areas where there is terracing, runoff speed could be reduced with increased infiltration, ultimately resulting in lower soil loss and sediment delivery.

Values for this factor were assigned considering local management practices and based on values suggested by Hurni (1985) and Eweg and Lammeren (1996) as shown in Table 6.1. Most of the data related to management practices were collected during field visits of each catchment in January to March, 2003. The presence and status of conservation activities were assessed with emphasis on the existing conditions of terraces and protected areas. Most of the catchments are well-terraced, mainly the upslope parts. However, most of the terraces are broken due to high runoff and/or livestock trampling.

Table 6.1: KCP factors adapted for this study (based on Hurni, 1985; Feoli et al., 1995; Machado et al., 1996a, b).

(Geomorphological unit): (Machado et al., 1996a, b)[1]	**K-factor**	**(Land cover): (Hurni, 1985)**	**C-factor**
Erosion remnants with soil cover	0.03	Dense forest	0.001
Erosion remnants without soil cover	0.01	Dense grass	0.01
Badlands	0.04	Degraded grass	0.05
Scarps/denudational rock slopes	0.02	Bush/shrub	0.02
Alluvial fans	0.04	Sorghum, maize	0.10
Alluvial plain and terraces	0.03	Cereals, pulses	0.15
Infilled valleys	0.03	Ethiopian Teff	0.25
		Continuous fallow	1.00
Management type (Hurni, 1985 and Eweg and Lammeren, 1996)	**P-Factor**		
Ploughing up and down	1.0	Protected areas	0.50
Strip cultivation	0.80	Ploughing on contour	0.90
Stone cover (80%)	0.50	Terraces	0.60
Stone cover (40%)	0.80		

6.3.5 Slope length and steepness (LS) factor

Terrain geometry and characteristic (slope, aspect, and curvatures) have significant impact on the spatial distribution of erosion/deposition (Moore and Burch, 1986; Mitasova et al., 1999; Desmet and Govers, 1996a). It is therefore essential to take account of the three-dimensional complex terrain through a landscape-based approach to fully capture the spatial distribution of erosion/deposition processes (Mitas and Mitasova, 1998a).

Data on terrain attributes can easily be derived using GIS and other associated hydrological models provided that sufficiently detailed and accurate DEMs are available. DEMs were constructed from existing contour maps of 1:50000 scale with a grid cell size of 10 m. The 10 m cell size was chosen because this cell size is considered to be a rational compromise between increasing resolution of grid size and the data volume needed for hydrological process modelling (Quinn et al., 1991; Zhang and Montgomery, 1994). During DEM construction, the spline function with drainage enforcement interpolation facility in the TOPOGRID (Hutchinson, 1989) was used to enforce flow tracing so that DEMs with minimum incidence of spurious depressions can be created (Hutchinson, 1989; Mitasova et al., 1995). After the DEMs were created for all sites, remaining pits were filled before any processing was undertaken, in order to route runoff and associated sediment to the catchment outlet without facing "unnecessary obstacles". The slope-length (L) and slope-gradient (S) factors were then computed following the procedures of the respective models as outlined below.

6.4 Model description

6.4.1 The Sediment Transport Capacity Index (STCI) Model

A number of hydrologically based, topographically derived indices appear to be powerful and useful for determining areas of land susceptible to various types of environmental hazards and degradation such as erosion, siltation and non-point source pollution (Moore and Nieber, 1989). Most of the hydrologic and erosion process models emphasize the importance of defining terrain-related variables in an objective and detailed manner to be able to capture processes at different scales and terrain configurations (Moore et al., 1991). One such model is the STCI proposed by Moore and Burch (1986) which is given as:

$$STCI = (m+1)\left[\frac{A_s}{22.13}\right]^m \left[\frac{\sin\beta}{0.0896}\right]^n \tag{6.7}$$

where A_s = specific upslope contributing area per unit length of contour; β = local slope gradient (degrees); *m* and *n* = empirical constants (slope length and angle coefficients).

Equation 6.7 shows that the first part of the equation determines how much water is accumulating from upstream areas and therefore identifies areas that contribute to overland flow, while the second part determines the speed at which overland flow moves downslope (Pallaris, 2000).

For all erosion models, the slope length (m) and slope angle (n) coefficients need to be calibrated for specific areas and for the specific prevailing type of flow and soil conditions (Foster, 1990; Moore and Wilson, 1992). Generally, larger values of slope-length exponent are associated with increasing concentrated flow and rill erosion.

When the dominant processes are sheet flow and interill erosion, the slope-length exponent approaches zero, since such erosion processes are independent of slope length (Meyer et al., 1975; McCool et al., 1987). Based on available literature, slope length and gradient coefficients of 0.5 and 1.3, respectively, were used for catchments that were more vulnerable to rilling and gully formation. For sites with good surface cover, where interill erosion dominated, slope length and gradient values of 0.4 and 1, respectively, were used (Moore and Wilson, 1992; Liu et al., 2000; Mitasova et al., 2001).

Equation 6.7 is based on the unit stream power theory and is more amenable to landscapes with complex topographies because it explicitly accounts for flow convergence and divergence through the A_s term (Moore and Burch, 1986; Moore and Nieber, 1989; Moore and Wilson, 1992). The upslope area is preferred over the slope-length approach at a catchment scale, since upstream area rather than slope-length is the key determinant factor of runoff above every point (Moore et al., 1991; Desmet and Govers, 1996a; Mitasova et al., 1997). Upslope contributing area (which replaces the L factor of (R)USLE) can be calculated by (Mitasova et al., 1996; Gallant and Wilson, 2000; Park et al., 2001):

$$A_s = \frac{1}{b_i}\sum_{i}^{N} a_i \mu_i \qquad (6.8)$$

where a_i = the area of ith grid cell; b = the contour width of the ith cell, which is approximated by cell resolution; μ_i = the weight depending upon the runoff generating mechanism and infiltration rates (assumed to be 1 here); N = the number of grid cells draining into grid cell i.

The specific catchment area (A_s) term can be calculated by knowing the number of upslope cells that drain to a particular cell downslope (Freeman, 1991; Quinn et al., 1991). Definition of the upslope area to a particular cell is based on the assumption that water flows from one node to one of eight possible neighboring nodes, either based on single flow or multiple flow algorithms (e.g., O´Callanghan and Mark, 1984; Freeman, 1991; Quinn et al., 1991; Desmet and Govers, 1996b).

Quinn et al. (1991), Desmet and Govers (1996b) and Park et al. (submitted) compared different flow algorithms to evaluate their impact on material flux and spatial distribution of soil properties. These studies and others have shown that the type of routing algorithm employed can have an impact on the upslope contributing area calculation and other secondary terrain attributes. In order to account for the role of both flow convergence and divergence on erosion/deposition processes, the multiple flow algorithm suggested by Freeman (1991) available in DiGem (Conrad, 1998) was used in this study.

6.4.2 The USLE2D model

In (R)USLE, slope length is defined as the horizontal distance from the origin of overland flow to the point where either the slope gradient decreases to a point where deposition begins, or runoff becomes concentrated in a defined channel (Wischmeier and Smith, 1978; Renard et al., 1997). However, in real two-dimensional landscapes, overland flow and the resulting soil loss depend on the area per unit of contour length contributing runoff to that point (Moore and Nieber, 1989; Desmet and Govers, 1996a). The upslope area-based calculation of an L factor will therefore differ considerably from that of the manually measured slope length-based L factor, because it is strongly affected by flow convergence and/or divergence (Desmet and Govers, 1995; 1996a). In order to account for complicated flow divergence and convergence patterns that are mostly inevitable in real landscapes, substituting the L factor component of the (R)USLE by upslope area was suggested (Moore and Burch, 1986; Desmet and Govers, 1996a; Mitasova et al., 1999).

To accommodate the condition on non-uniform slopes in natural landscapes, Foster and Wischmeier (1974) subdivided the slope into a number of segments with uniform slope gradient and developed an equation to calculate the LS factor for each component. This equation was then expanded for two-dimensional topography by substituting the unit contributing area for the slope length, as each grid cell may be considered as a slope segment having a uniform slope (Desmet and Govers, 1996a). Replacing slope length with unit contributing area at the inlet and outlet of a grid cell, the slope-length factor L may be given as (Desmet and Govers, 1995, 1996a):

$$L_{i,j} = \frac{As^{m+1}{}_{i,j-out} + As^{m+1}{}_{i,j-in}}{(As_{i,j-out} - As_{i,j-in})(22.13)^m} \tag{6.9}$$

where $L_{(j,j)}$ = the slope-length factor for the grid cell with coordinates (i, j); $As_{(i,j-out)}$ = contributing areas at the outlet of a grid cell with coordinates (i, j) (m^2); $As_{(i,j-in)}$ = contributing areas at the inlet of a grid cell with coordinates (i, j) (m^2 m^{-1}); m = the slope length-exponent of the LS factor of the USLE.

Data used to develop the RUSLE involved slopes up to 18% only (McCool et al., 1989). However, most cropped watersheds can have a slope gradient in excess of more than 30% (McCool et al., 1989; Liu et al., 2000). Nearing (1997) therefore proposed a logistic equation expressed as a single continuous function of slope gradient for computing the steepness (S) component of the LS factor as given below:

$$S = -1.5 + 17 \Big/ \left[1 + \exp(2.3 - 6.1 \sin\theta)\right] \tag{6.10}$$

where S = slope steepness factor and θ = slope angle (degrees).

The USLE2D model provides an opportunity to employ different slope-length coefficients. Depending upon the type of flow and prevailing erosion, the McCool et al. (1987) rill = interill or rill > interill equation was applied in this study. The model also provides a possibility of estimating soil erosion based on different routing algorithms such as steepest descent (single flow), multiple flow and flux decomposition algorithms (Freeman, 1991; Quine et al., 1991; Desmet and Govers, 1995, 1996b). The multiple flow algorithm was used in this study to make it consistent with the flow algorithm adopted for the other models.

6.4.3 The Unit Stream Power based Erosion/Deposition (USPED) model

The above models have one important limitation in that they are not able to determine areas of possible sediment deposition (Moore and Burch, 1986; Mitasova et al., 1999; Van Oost et al., 2000). Such models can therefore be applied with the assumption that transport capacity exceeds detachment capacity everywhere, and sediment transport is detachment-capacity limited (Mitasova et al., 1999, 2001). They may thus be properly applied only to areas experiencing net erosion by excluding depositional areas (Moore and Burch, 1986; Mitas and Mitasova, 2001). In order to predict both areas of erosion and deposition, models that can take into account deposition process that may occur when the energy of transporting agent is no longer sufficient to transport soil particles are necessary. The USPED model (Mitasova et al., 1997, 1999, 2001) can be used to predict the spatial distribution of areas with topographic potential for erosion or deposition, based on the unit stream power and directional derivatives of the surface representing the sediment transport capacity.

The USPED model predicts the spatial distribution of erosion and deposition rates for steady state overland flow with uniform rainfall excess conditions for transport-limited cases of erosion processes (Mitasova et al., 1997, 1999). It is derived from the sediment transport capacity-based LS factor of Moore and Burch (1986) and Moore and Wilson (1992) by refining it to use continuous representation of sediment transport capacity and calculate directly its derivative, instead of using the originally suggested finite difference approach (Mitasova et al., 1999). For transport-limited case of erosion, the model assumes that the sediment flow rate (qs) is at sediment transport capacity (T) based on Julien and Simons (1985):

$$|qs| = T = K_t |q|^m [\sin \beta]^n \tag{6.11}$$

where K_t = transportability coefficient, which is dependent on soil and cover; q = water flow rate approximated by upslope contributing area (*As*); *m* and *n* = constants that vary according of type of flow and soil properties; β = slope.

Because there were no experimental data available to develop parameters for the USPED, the R(USLE) parameters were used to incorporate the impacts of soil and cover on erosion/deposition processes. It was therefore assumed that sediment flow can be estimated as sediment transport capacity (Mitasova et al., 1999, 2001):

$$T = RKCPAs^m (\sin b)^n \tag{6.12}$$

where *RKCP* = the original R(USLE) variables; *As* = unit contributing area (replacement of L factor); *b* = slope angle; *m* and *n* are empirical coefficients that control the relative impact of water and slope terms and reflect different erosion patterns for different types of flow. Coefficients for m and n vary from 1.6 - 1.4 and 1.4 - 1.0, respectively, depending on the type of flow (e.g., Mitasova et al., 2001).

The above equation defines the availability of stream power for sediment transport and allows the detection of areas with high mass transport capacity. The net erosion/deposition is then estimated as the divergence of the pattern T in the computation domain with planar coordinates (x, y) (Mitasova et al., 1997). In a three-dimensional GIS, it is possible to account for other than parallel patterns of sediment flow lines, which may actually be converging or diverging from the given computational cell. This is accomplished by incorporating a topographic parameter describing profile terrain curvature in the direction of the steepest slope and the tangential curvature in the direction perpendicular to the profile curvature. These topographic parameters are computed from the first and second order derivatives of terrain surface, approximated by regularized spline with tension (Mitasova and Mitas, 1993). The functionality of the USPED is given as (Mitasova et al., 1999, 2001):

$$USPED = div(T.s) = \frac{\partial(T * \cos\alpha)}{\partial x} + \frac{\partial(T * \sin\alpha)}{\partial y} \tag{6.13}$$

where s = a unit vector in the flow direction; α = aspect of the terrain surface (in degrees).

This terrain-based model probably represents a superior approach to simulating the impacts of complex terrain and various soil-and land-cover changes on the spatial distribution of soil erosion/deposition (Wilson and Lorang, 1999; Wilson and Gallant, 2000). It is more appropriate for landscape scale erosion modelling, especially when the locations of both areas with erosion risk and deposition potential are important (Mitasova et al., 1999, 2001). The USPED model has also the capacity to predict the spatial pattern of gullies and estimate their soil loss potential (Mitasova et al., 2001).

6.5 Sediment delivery ratio (SDR) estimation

SDR is a measure of sediment transport efficiency, which accounts for the amount of sediment that is actually transported from the eroding sources to a catchment outlet compared to the total amount of soil that is detached over the same area above the outlet (Walling, 1983; Lu et al., 2003). Adjustment of gross soil loss values for the SDR is necessary, since gross erosion from catchments (STCI and USLE2D) may not necessarily reflect sediment delivery at outlets unless deposition along the path from source to continuous streams is accounted for (Walling, 1983, 1990).

While established methods are available for estimating the rate of soil loss from farm-size areas, there is no generally accepted method for determining the percentage of eroded sediment that will be delivered to the basin outlet (Morris and Fan, 1998). Haan et al. (1994) pointed out that the degree of understanding of SDRs is probably less than any other areas of sedimentation. The magnitude of the SDR for a particular basin is influenced by a wide range of geomorphological and environmental factors including the nature, extent and location of the sediment sources, relief and slope characteristics, the drainage pattern and channel conditions, vegetation cover, land use and soil texture (Walling, 1983; Dickinson et al., 1986, 1990). Generally, in environments where terrain is pronounced, erodibility is high, surface cover is poor and dense gully connectivity, the SDR is expected to be high (Krishnaswamy et al., 2001). The SDR may also increase if the proportion of basin affected by high erodibility and erosivity or alluvial sediment remobilization increase as one goes downstream (Walling, 1983; Krishnaswamy et al., 2001).

If data on sediment yield to outlets and gross soil erosion from upslope of outlets are available, SDR can be calculated by relating the annual sediment deposition to outlets (reservoirs) with annual gross erosion from upslope catchments:

$$SDR = \frac{SY}{E} \tag{6.14}$$

where SY = annual sediment deposition in a reservoir (outlet) and E = the annual gross soil loss from the corresponding catchment.

Equation 6.14 gives single SDR value for the whole basin which may not be representative for the different landscape positions. A distributed SDR estimation may, therefore, be necessary to estimate the sediment delivery efficiency of the different landscape positions. One simple approach to achieve this could be by using the equation given by Hession and Shanholtz (1988):

$$SDR_i = \left(\frac{HD_i}{SL_i} \right) 10\,\hat{} \qquad (6.15)$$

where SDR_i = SDR of a land cell (subunit); HD_i = elevation difference between a land cell at a given point/subunit and the associated main stream outlet cell; SL_i = length of the flow path between the inlet of a subunit and the main channel outlet.

To apply equation 6.15 and estimate distributed SDR values, each catchment was first subdivided into different hydrological subunits. The SDR was calculated for each subunit, which was then used to adjust the gross soil loss from each pixel of the associated subunit. An average of SDR considering all subunits gives an approximate SDR value for the whole of the catchment. The SDR calculation made using equations 6.15 can only be used as approximations and it may not be accurate enough for strict application as it does not incorporate detailed terrain factors that may dictate erosion/deposition processes. The role of intermediate storages in soil redistribution need to be taken into account to determine reasonably accurate SDR values (Dikau, personal com.).

6.6 Data collection to evaluate model results

Different approaches can be used to evaluate model results including (1) sediment yield data at outlets (e.g., Moore and Foster, 1990); (2) data from representative erosion plots (e.g., Nearing, 1997); (3) field measurement of rill erosion networks (e.g., Auzet et al., 1993; Quine et al., 1997); (4) rill and gully volumes and thickness of sediment deposits (Takken et al., 1999); (5) thickness of soil profile and depth of buried soil (e.g., Desmet and Govers, 1995; and (6) ^{137}Cs-based soil redistribution data (e.g., Busacca et al., 1993; De Roo and Walling, 1994; Montgomery et al., 1997; Turnage et al., 1997; He and Walling, 2003; Walling et al., 2003).

Each of these methods has its own limitations, including representativeness, spatial and/or temporal scale difference, accuracy in estimation and time consumption (e.g., De Roo, 1996). Comparison of model results with outlet-based sediment yield estimates may not provide information on the capacity of the model to predict spatial patterns (e.g., Jetten et al., 1999; Takken et al., 1999; Jetten et al., 2003; Walling et al., 2003). Use of measured data from erosion plots may not be suitable, since the plot data may not account for all the variability within the catchments (e.g., Nearing et al., 1999). The use of measured rill and gully volume and thickness of sediment deposit may have limited application to bigger catchments, since measuring rill/gully volumes for distributed points could be time consuming. The soil profile-based model evaluation could be problematic, as the soil thickness differences could be functions of several years of erosion and deposition processes. The use of ^{137}Cs-based model evaluation may not be effective due to differences in the spatial resolution between the ^{137}Cs data and the model-predicted output (De Roo and Walling, 1994) and the effect of tillage translocation (Quine, 1999). In this study, a combination of approaches was applied to capture the strength of the different methods for model evaluation. Brief descriptions of the major approaches used are described below.

6.6.1 Caesium-137 data collection and analysis

The use of fallout ^{137}Cs measurements affords an essentially unique means of assembling the spatially distributed information on rates of soil redistribution within a catchment required to assess the results of distributed erosion and sediment delivery models (Turnage et al. 1997; Stefano et al., 1999; Walling et al., 2003). To this end, transect-based ^{137}Cs data were collected for two converging hillslopes in the Maidelle catchment (Figure 6.3). The hillslopes selected were simple but with good representation of topographic positions where erosion and deposition could occur. The transects were roughly 60 m apart, and the sampling points along the transects were at a spacing of about 60 m. At each sampling site and transect, 2 replicate bulk undisturbed soil samples were collected using cylinder corer with a diameter of 9 cm from a depth of up to 30 cm. In order to have a reference against which potential eroding and aggrading sites could be compared, ^{137}Cs reference data were collected from nearby locations of within 1-3 km of the ^{137}Cs sites. Since it was not possible to find undisturbed sites with forest cover on appropriate slopes, two of the five reference sites were located on a cultivated field at an upland plateau of zero slope.

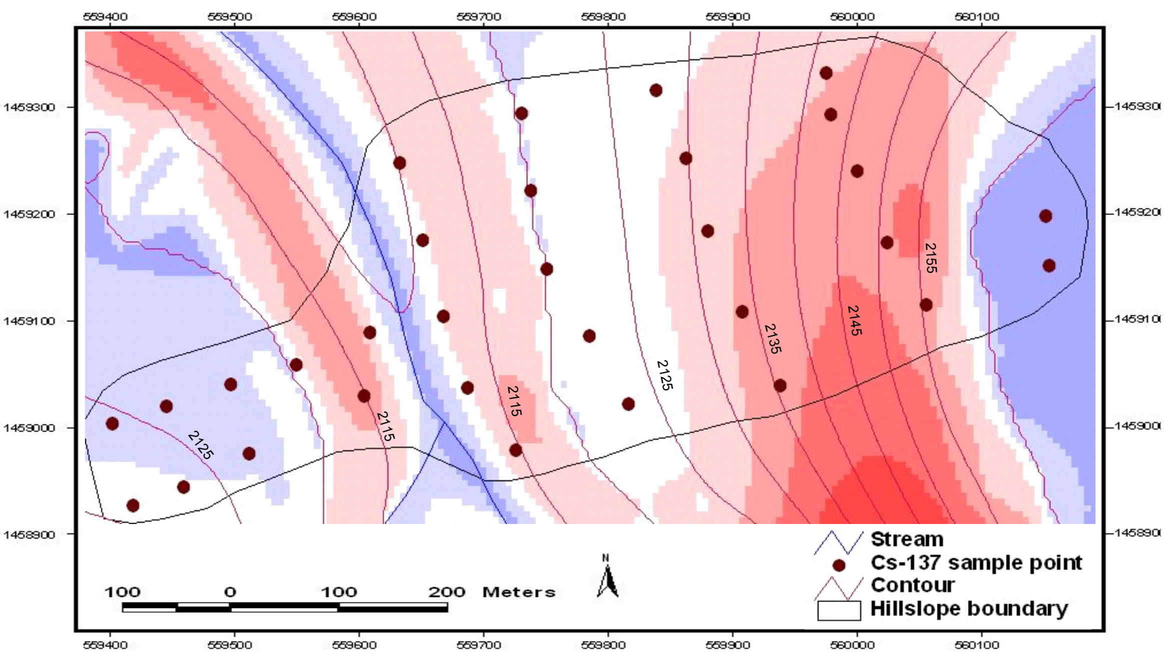


Figure 6.3: Distribution of ^{137}Cs sample points within Maidelle catchment in Tigray, N. Ethiopia. The ^{137}Cs sample locations are displayed on slope as background

The sampling program yielded a total of 36 samples, out of which 5 were from the reference sites. The samples were oven-dried, disaggregated, sieved through a 2 mm mesh and homogenized. Each sample was weighed before and after drying and 300 g of samples from the < 2 mm fraction of each sample were sealed in a plastic container and dispatched for laboratory analysis. The ^{137}Cs samples were analyzed at the laboratory of the University of Gottingen, Germany.

The laboratory result of the levels of ^{137}Cs activity was reported in Becquerels per kilogram (Bq kg^{-1}). This was converted to ^{137}Cs inventory per unit area (Bq m^{-2}) using the soil bulk density and the cross-sectional area of the core. The ^{137}Cs percentage residual was also calculated by comparing values of inventories and reference sites based on Walling and Quine (1993):

$$CPR = ((CPI - CRI) * 100) / CRI \tag{6.16}$$

where CPR = ^{137}Cs percentage residual; CPI = ^{137}Cs point inventory; CRI = ^{137}Cs reference inventory.

Negative and positive residuals indicate ^{137}Cs loss and gain, respectively. Pattern of ^{137}Cs gain and loss broadly reflect pattern of soil erosion and deposition, respectively (Walling and Quine, 1993). The ^{137}Cs residuals, however, do not show the quantitative rate of soil redistribution. In order to use the ^{137}Cs inventory to estimate rates of soil redistribution, the ^{137}Cs loss and gain were converted to quantitative rates of soil erosion and deposition using the Proportional Model (PM) and the simplified Mass Balance Model (MBM1) developed by Walling and He (2001).

Once the quantities of soil loss and gain for each sample location were determined, average soil loss and sediment delivery ratio of each transect and the two hillslopes were estimated. The values of soil loss and gain of each sample point were also interpolated to produce spatially distributed soil erosion/deposition maps (e.g., Chappell et al., 1998; Walling et al., 2003). The rates and spatial patterns of soil redistribution as evaluated from ^{137}Cs were then compared with the rates and spatial patterns of erosion and erosion/deposition predicted by the models.

6.6.2 Soil profile data

Different studies show that soil profile data such as presence and thickness of alluvial/colluvial deposits and degree of truncation of the top soil horizon can be used to assess the performance of models (e.g., Desmet and Govers, 1995; Mitasova et al., 1997; Turnage et al., 1997). This approach was applied to evaluate the results of the models used in this study. For this purpose, areas where possible erosion and deposition processes were expected and those considered relatively stable were selected, and soil profile data related to the truncation level of the A horizon, presence and corresponding thickness of buried soils and alluvial/colluvial deposits were assessed for selected sites in two catchments (Gerebmihiz and Laelaywukro). These data were then compared with the soil loss predictions made by each model. The main purpose was to evaluate whether the spatial pattern of erosion (STCI and USLE2D) and erosion/deposition (USPED) predicted by models correlate with the depth of soil profile data and to semi-quantitatively verify the performance of the models.

6.6.3 Similar Erosion Risk Potential Units (SERPUs)

Collection of spatially distributed data to evaluate the results of spatially distributed models applied at the watershed scale is usually expensive and difficult (Stefano et al., 1999; Walling et al., 2003; Jetten et al., 2003). It is more expensive and less practical to collect distributed ^{137}Cs data for larger catchments dissected by deep and wide gullies. The soil profile data may also not adequately handle the spatial variability of erosion/deposition processes. Therefore, methods of evaluating spatially distributed models applied at the catchment scale using independent data collected with relatively minimum cost and acceptable accuracy need to be devised. In this study, the concept of Similar Erosion Risk Potential Units (SERPUs) was introduced to represent terrain units with similar erosion risk levels due to similarity in basic terrain attributes.

Studies by Flügel (1996, 1997); Flügel et al. (1999) and Marker et al. (2001) show that different erosion process dynamics are linked to certain associations of system component properties. Entities with the same erosion process dynamics consequently consist of certain associations of system characteristics and system inputs whereby a drainage system can be perceived as an assembly of spatial process entities with different potentials (Hochschild et al., 2003). Fargas et al. (1997) developed a method to identify sites of sediment emission risk through qualitative ratings of basic terrain data that can be related to erosive processes. Recently, hydrologically similar surfaces (HYSS), which are distributed homogeneous units within a catchment based on key runoff producing variables of land use, slope and geology, resulting in similar runoff response during storms, were conceptualized by Bull et al. (2003). The above concepts revolve around systematically dividing catchments based on common attributes, so that units with similar potentials, constraints and processes can be found.

The SERPUs in this study were derived based on the assessment of basic environmental factors of catchments that define the susceptibility to erode and connectivity to deliver. The main aim was to present a simple method of predicting sediment source areas using runoff potential produced by combining key catchment attributes in a GIS and performing simple overlay analysis. Since the SERPUs are derived based on terrain attributes that control erosion processes, they can represent potential areas of similar erosion problems and serve as proxies to erosion potential maps. They could, therefore, be used to evaluate model results.

To produce the SERPUs, the catchments were categorized based on their runoff and sediment production potential mainly considering slope, lithology, land-cover types, land-cover condition, and gully erosion. Slope steepness was considered to serve as a proxy to estimate erosivity potential, while surface lithology was used as a proxy to estimate erodibility potential. Surface cover enables to determine the frictional resistance of terrain units based on the degree of surface protection, while surface cover condition reflects the intensity of degradation. Finally, gullies were considered to account for the degree of catchment connectivity and therefore efficiency of sediment delivery potential. Each landscape unit within a catchment was classified into five categories of erosion potential (very high, high, medium, low, very low) considering the four attributes (slope, lithology, land-cover type and land-cover condition). A systematic combination of the four maps with the spatial distribution of gullies in a GIS and a simple overlay analysis allowed the categorization of landscape units into similar runoff and erosion potential. The resulting maps were compared with erosion risk maps based on the distributed erosion models. The procedures employed to derive the variables that ultimately defined the SERPUs are discussed below.

a. Catchment stratification based on slope

The slope maps of the catchments were classified into potential runoff assuming that on steeper slopes the soils are likely to be thinner and the flow velocities greater, which results in high runoff. On flat slopes, runoff thresholds will be high, since water is likely to pond and infiltrate, resulting in little or no runoff (Bull et al., 2003).

Considering other variables to be constant, it was assumed that slope less than 5° are likely to produce low amounts of runoff followed by slopes 6 - 10°, 11 - 15°, 16 - 25° and > 25°. The slope classes were ranked from 1 to 5, with 1 representing slopes with the lowest runoff potential and 5 the highest (Table 6.2). The classification is based on the premise that increasing slope steepness increases runoff and erosion potential.

b. Catchment stratification based on lithology

The potential runoff and sediment yield of different lithologic groups was estimated based on their material composition and the sensitivity to weathering of different lithologic surfaces (Fargas et al., 1997; Martinez-Mena et al., 1998). Generally, fine-textured, poorly permeable soils of low organic carbon content show greater runoff coefficients and lower runoff thresholds than more permeable, coarser textured soils (Bull et al., 2003). Areas dominated by sandstone, basalt, and metavolcanics can have high permeability and generally contain less loose materials that can be transported by water and therefore do not yield much sediments assuming that weathering processes are minimal. On the other hand, shale/marl, siltstone and clay-stone-dominated areas could have low permeability and low infiltration capacity, which encourage runoff and sediment yield (Lahlou, 1988; Woodward, 1995; Fargas et al., 1997; Mills, 2003).

Based on the above premises, sandstone-and basalt- dominated landscape units, which can have generally high secondary permeability and hence high infiltration capacity, were ranked to have very low and low runoff potential and sediment yield. Dolerites, which are found scattered in some of the catchments, were characterized to have medium to high permeability depending on the degree of fracturing. Limestone and siltstone were generally characterized as having medium infiltration and runoff potential. Sites with alluvial/colluvial materials were categorized to generate medium to high runoff. Finally, shale- and marl- dominated landscapes were classed into high runoff and sediment yield categories. Table 6.2 shows the ranks in terms of sediment yield potential of the different lithologic types in the study catchments.

c. Catchment stratification based on surface cover

Land-cover types play a significant role in the variability of infiltration capacity and runoff potential. When land is covered with vegetation, total roughness can be high, which can increase the runoff threshold. When the land has poor surface cover, its roughness decreases, ultimately resulting in a lower runoff threshold and a quick response to rainfall (Lasanta et al., 2000; Bull et al., 2003). Overgrazing can result in surface crusting and increase runoff potential (e.g., Boardman, 2003). Dense surface cover increases surface roughness and runoff threshold (Bull et al., 2003). Forest parcels do not generate runoff and are therefore hydrologically isolated, while arable land areas can be considered as being hydrologically continuous (Desmet and Govers, 1996a).

Accordingly, areas with dense cover are considered to have low runoff potential, with high infiltration. Bushes and shrubs were assigned with medium runoff potential while agricultural cropping lands were considered as sites having high runoff potential, depending on the growth stage and the time when the runoff measurements are made. Barren degraded lands are assigned with very high runoff potential. Table 6.2 shows the scores given to the major land-cover types identified.

Table 6.2: Classification of parameters used in the overlay analysis to generate SERPU

Rank	**Parameter**			
	Slope	**Lithology**	**Land cover**	**TSAVI***
1	0- 5°	Sandstone, metamorphic, basalt	Dense cover/enclosures	> 0.1
2	5 – 10°	Hard rocks of lime stone, dolerites	Bushes/shrubs	0.04 – 0.1
3	10 – 15°	Limestone intercalated with shale	Scattered bushes/shrubs	0–0.04
4	15 – 25°	Colluvium/alluvium deposits	Cultivated/cropland	-0.02 – 0
5	> 25°	Shale, marl, debris flow	Degraded bare land	< - 0.02

* *Transformed Soil Adjusted Vegetation Index: high values indicate good surface cover and low ones show poor surface cover.*

d. Catchment stratification based on condition of surface cover

Land-cover maps generated from satellite images may not be able to show the condition of the surface cover. An effort was thus made to distinguish areas with different states of surface cover using a vegetation index. The transformed soil adjusted vegetation index (TSAVI), which significantly reduces the effect of soil background reflectance (Purevdorj et al., 1998a, b) and is conducive to map degradation level (Hochschild et al., 2003), was utilized to delineate the differences in the density and condition of vegetation cover. The TSAVI is considered the very efficient for calculating vegetation cover ratios in semi-arid environments of sparse vegetation and provides results that are in accordance with *in-situ* measurements (Purevdorj and Tateishi, 1998; Baret et al., 1989, 1993; Flügel et al., 2003).

The TSAVI maps were used to assess the condition of surface cover and "degradation level" that can be associated with different runoff and sediment yield potential. Degraded areas tend to have low TSAVI and high runoff potential compared to well protected and less degraded areas. The results of the TSAVI were categorized into five classes, with very high negative values representing very poor surface condition and positive indicating good surface conditions (Table 6.2). Natural breaks of the TSAVI histogram were used to define each TSAVI class (Table 6.2).

e. Catchment characterization based on patterns of gullies

Field observation and data from local experts and farmers indicate that gully erosion is one of the major processes of soil loss in most of the catchments. Catchment connectivity due to gullies encourages efficient sediment delivery. Gullies could also contribute sediment due to bank collapse. Automatic delineation of ephemeral gullies from DEMs combined with results of erosion models can improve the prediction of the most critical areas of erosion within a catchment (Desmet and Govers, 1996b). Gullies were therefore used as one component of the SERPUs to incorporate their role in predicting potential areas of sediment production and delivery.

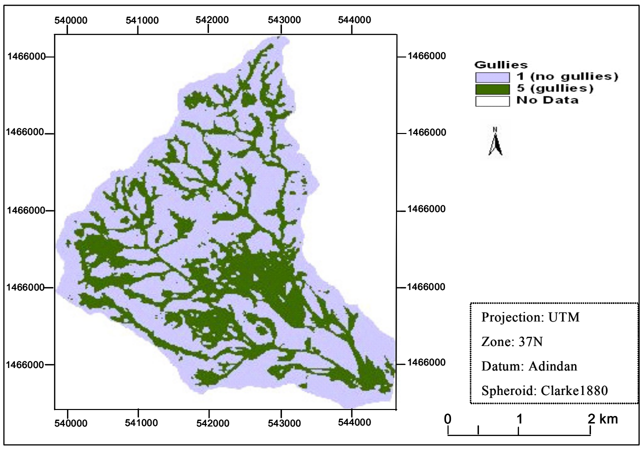
In order to evaluate the significance of gullies to total soil loss and predict their spatial pattern within the catchments, the potential location of gullies was analyzed following the method proposed by Thorne et al. (1986) and Moore et al. (1988). The potential location of ephemeral gullies may be predicted when both of the following two conditions are satisfied:

$$A_s \tan\beta > 18 \tag{6.17}$$

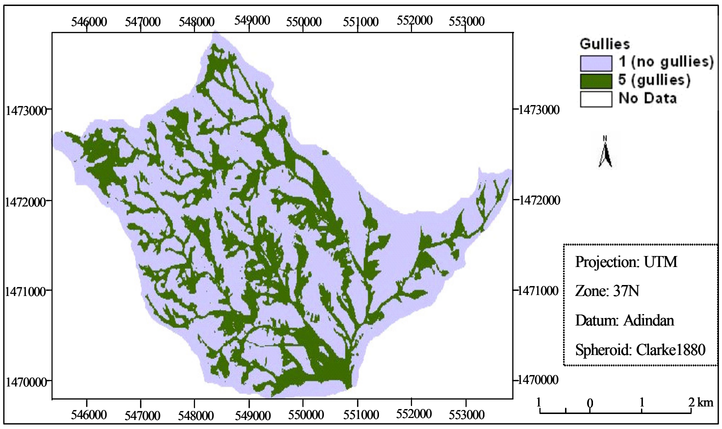
$$\ln\left(\frac{A_s}{\tan\beta}\right) > 6.8 \tag{6.18}$$

where A_s = the unit contributing area (m^2 m^{-1}); β = the local slope (tan); $A_s \tan\beta$ and $\ln(\frac{A_s}{\tan\beta})$ = the stream power index and the wetness index, respectively (Beven and Kirkby, 1979).

Figure 6.4 shows the possible location and spatial distribution of gullies based on the combination of the above two terrain indices. The locations representing gullies were coded as 5 while those with no gullies were coded as 1 (Figure 6.4). The results of the above indices were tested using locations of gullies collected during field surveys. There is a good agreement between the two, despite minor differences related to small ephemeral gullies mainly located on the upslope parts of the catchments.



(a)



(b)

Figure 6.4: Potential location of ephemeral gullies based on gully erosion indices for two example catchments (a) Adikenafiz and (b) Gerebmihiz in Tigray, N. Ethiopia

f. Deriving the SERPUs

A simple GIS overlay was used to combine the above maps and identify the spatial patterns of high risk areas of erosion and sediment delivery potential (Figure 6.5). During the processes of ranking and overlaying, the following limitations were noted: (1) that there was no weight differentiation in the rank of each category for each factor, i.e., it was assumed that ranks assigned to factors have equal weight (rank 1 for factor 1 has equal weight to rank 1 for factor 2, and so on); (2) that the ranks were not field calibrated and not meant to show soil loss rates rather than relative differences of factors across landscapes; (3) that the threshold values for the compound gully indices were not calibrated for conditions of the study areas. Since the main interest was the identification of landscape positions with different sensitivity to erosion due to a combination of basic terrain attributes, the above assumptions may not have marked impact on the interpretation of results. In addition, the main goal was not to derive soil loss rates based on the SERPUs, but rather to define locations within catchments where soil loss and delivery potential was higher due to similar geomorphic evidences.

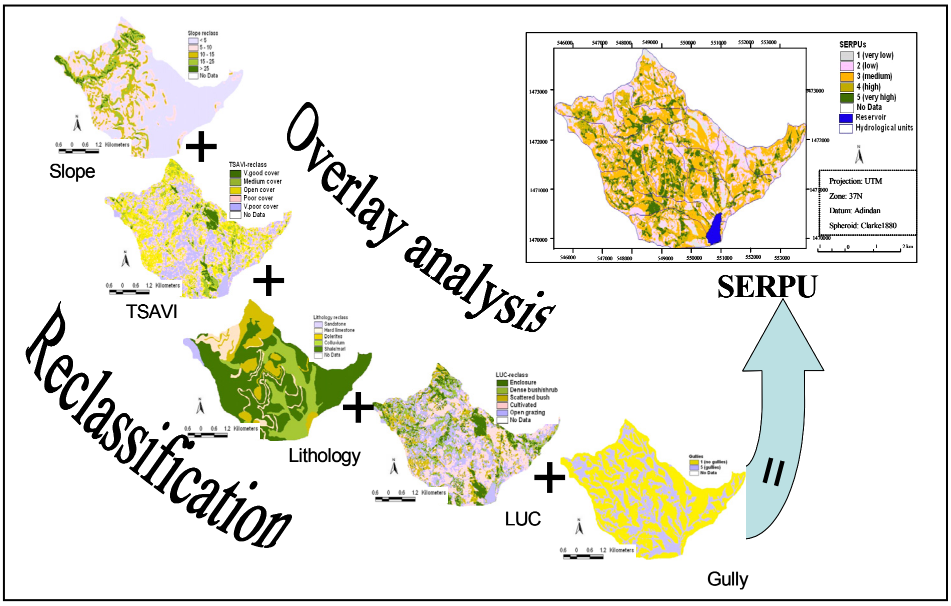
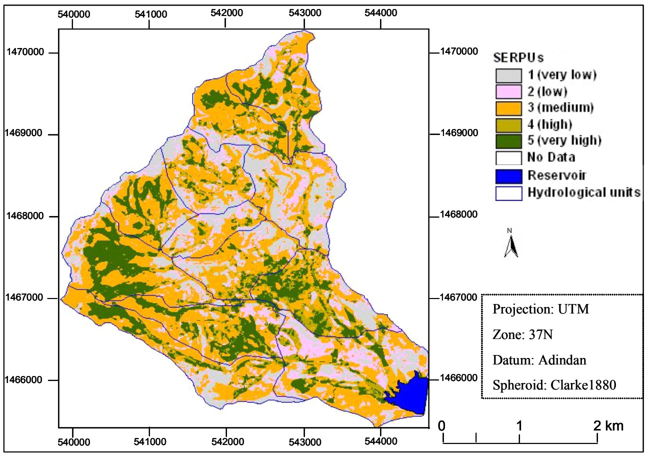


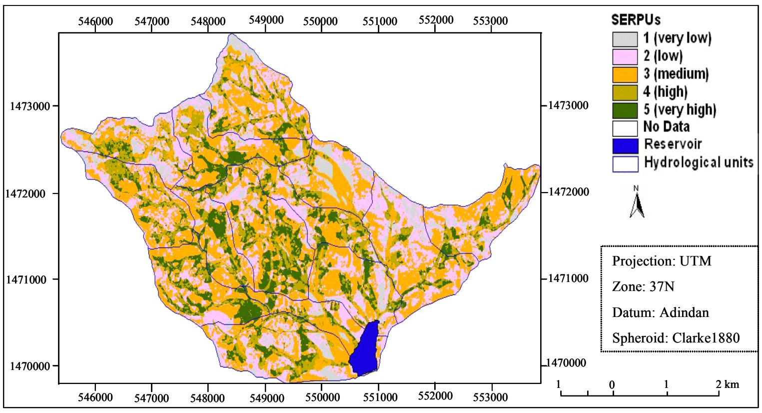
Figure 6.5: Reclassification and overlay steps conducted to generate SERPUs (see table 6.2 for classes)

Bearing in mind the above weaknesses and strengths, the maps produced in the above steps (slope, land-cover type, land-cover condition and lithology) with classes from 1 to 5 were overlaid (addition), resulting in a continuous map of runoff potential with values ranging from 5 – 20. Addition was used to combine the maps in order to keep the size of classes smaller and manageable. After the overlay was performed, each of the maps was reclassified into five categories of runoff/erosion potential (very high, high, medium, low and very low) using equal interval threshold values of 5-7, 8-10, 11-13, 14-16, 17-20. Each category was coded from 1 to 5. Higher values indicate locations with high potential runoff/erosion due to the suitability of the runoff generating factors.

To derive the final SERPU for each catchment, which also considers sediment delivery potential, the five category runoff/erosion potential maps (class 1 to 5) of each site were combined with the gully erosion potential maps (class 1 and 5) resulting in maps with continuous values ranging from 2 (very low category with no gully) to 10 (very high category with gully). The SERPUs were finally reclassified into five categories of runoff/erosion potential (Figure 6.6) using threshold values of 2-3 (very low), 4 (low), 5-7 (medium), 8 (high), and 9-10 (very high). The classes were based on the nature of the possible combinations of the above maps. For instance, in conditions where high erosion potential due to the four factors (Table 6.3) and gullies coincide, the new reclassification will result in a high category.



(a)



(b)

Figure 6.6: Areas susceptible to different levels of erosion risk based on SERPUs for two example catchments (a) Adikenafiz and (b) Gerebmihiz in Tigray, N. Ethiopia

The final SERPUs, based on key factors of erosion and gully connectivity, were considered proxies for potential sediment source and delivery. Areas with high values represent locations where sediment availability and transport capacity are not limiting. The SERPUs indicate the relative sensitivity of each cell with respect to key parameters that affect erosion and provide rough information about the critical zones of soil loss and potential delivery. Despite the fact that it is not possible to attach adequate physical meaning to the ranks (reclassified maps) of each factor, the final SERPUs can serve to assess the spatial patterns of erosion risk areas and help as an independent distributed data source to evaluate the results of the distributed models.

6.6.4 Catchment characterization based on erosion sensitivity scores

Since many of the processes and factors that influence erosion are well known, it is possible to rank individual factors that indicate susceptibility to erosion and derive a series of erosion indicators (Reid and Dunne, 1996; Kirkby, 1999). A field-based ranking procedure was designed to characterize catchment subunits into different categories of erosion and sediment yield potential based on evidence of erosion and degree of catchment connectivity. This process helps to identify areas that are active sources of sediment and efficiently deliver to adjacent streams and reservoirs.

Before characterization, each catchment was first divided into different hydrological subunits using DEMs and drainage networks. Field visits were then conducted to assess the sediment source and delivery potential of each subunit considering the factors shown in Table 6.3. The list of factors shown in the table is based on the terrain attributes (geomorphic evidences) necessary to describe the on-site sediment production and off-site delivery potential of subunits. The factors were associated with ordinal ranks of high, medium and low scores, which were used to evaluate the importance of single or multiple factors. Scores were assigned for each factor in each subunit and the summation of the score of factors enabled identification of the subunits with the highest erosion risk and delivery potential. Evaluating the factors with high scores of each subunit also enables identifying the relative significance of each catchment attribute.

After the total score of each subunit was calculated, the results were compared with soil loss values predicted by the models. The model whose soil loss estimate corresponded well with the field-based erosion risk potential of subunits was considered to be more useful to reflect the reality of the study sites. Since field characterization is relatively less error prone compared to other measurements, it can well serve to assess the results of models. Such approaches were applied in different studies to validate models (e.g., Svorin, 2003; Vigiak, et al., 2005) or identify hot-spot areas of erosion (e.g., Coleman and Scatena, 1986; Kirkby, 1999).

Table 6.3: Terrain attributes and scores for catchment characterization in terms of sediment sources and delivery potential in Tigray, N. Ethiopia

	Hillslope Dominant Attribute - on-site erosion	**Possible score**		
		3	**2**	**1**
1	Surface cover (condition, density)	Poor	Medium	Good
2	Level of degradation (evidences of erosion)	High	Medium	Low
3	Position in relation to streams/gullies[1]	Near	Medium	Far
4	Availability of material for detachment	High	Medium	Low
5	Average slope steepness	Steep	Medium	Gentle
6	Shape of sub-catchment[2]	Convex	Linear	Concave
7	Presence and extent of depositional sites	Low	Medium	High
8	Presence and intensity of other "disturbances"[3]	High	Slight	None
Total				
	Gully/stream dominant attribute - off-site delivery			
1	Drainage network (density of gully/stream)	High	Medium	Low
2	Status of gullies/streams (stability, collapse)[4]	Severe	Slight	None
3	Average slope of gully/stream path	Steep	Medium	Gentle
4	Evidences of deposition at gully/stream floor[5]	Low	Medium	High
5	Degree of meandering of flow[6]	Low	Medium	High
6	Degree of disturbance by livestock/cultivation[7]	High	Medium	Low
7	Conservation practices	None	Medium	High
8	Average distance to reservoir	Near	Medium	Far
Total				

[1]*Proximity to permanent stream channels/gullies as proxy to sediment delivery potential.*
[2] *Dictates accelerated or decelerated flow.*
[3] *The presence and, if so, role of "disturbances" such as roads, construction sites, and the likes.*
[4] *Removal of sediment adjacent to streams due to stream channel/gully migration plus evidences and severity of gully collapse.*
[5] *Deposition of materials that can obstruct and retard flow as well as fine sediments.*
[6]*The more the stream/gully meanders, the more it may deposit sediment at "ox-bow" positions.*
[7]*Role of cultivation up to the very edge of gullies and grazing on gully edges/floors as well as the significance of animal burrowing.*

6.7 Results

6.7.1 Annual soil loss rate

The predicted annual rates of soil losses for each of the four catchments based on the three models are presented in Table 6.4. Generally, all models predicted higher soil loss rates than the maximum tolerable soil loss rate of 18 t ha^{-1} y^{-1} estimated for the country

(Hurni, 1985). Only the USPED predicted slightly lower than the maximum tolerable rate for Laelaywukro catchment. If an average annual soil generation rate of 6 t ha^{-1} y^{-1} (Hurni, 1983a,b) is considered, the soil loss rates estimated by the models for most of the sites could still be considered beyond the acceptable level. More than 35% of each catchment experiences soil loss rates of greater than 25 t ha^{-1} y^{-1}. An exception is Laelaywukro, where a little less than 20% of the catchment experiences such soil losses based on the USPED model. The high soil loss rates show that the current cultivation practices in these environments should not be continued without necessary management interventions.

Table 6.4: Mean annual soil loss rate (t ha^{-1} y^{-1}) based on 3 erosion mmodels in selected catchments of Tigray, N. Ethiopia.

Site	STCI	USLE2D	USPED	Mean	CV (%)
Adikenafiz	82.5[1]	41.6	51.0	58.05	36.6
Gerebmihiz	74.6[2]	35.7	42.7	51.0	40.7
Laelaywukro	30.2	40.0	13.8	28.0	47.3
Maidelle	29.5	20.6	26.3	25.5	17.7
Mean	54.2	34.5	33.5		
CV (%)	52.2	27.8	50.0		

CV – coefficient of variation

[1, 2] show that when 1% of the sites with soil loss rate of more than 500 t ha^{-1} y^{-1} are excluded, mean soil loss values reduce to 65 and 62 t ha^{-1} y^{-1}, respectively.

The mean soil loss values of the different models are influenced by some extreme soil loss values. To avoid the effect of extreme values in the estimation of mean soil loss rates, it may be necessary to mask the areas with such values and exclude them from the calculation (Mitasova et al., 2001). For example, if about 1% of the sites with very high erosion values are excluded, the mean annual soil loss rates could drop by over 20% (Table 6.4). However, excluding the entire area with very high soil loss values could eliminate the real contribution of some areas as sediment sources. Since the sites with extreme values are mostly associated with gullies, excluding them would underestimate their contribution to catchment erosion and reservoir siltation.

Most of the models predicted high rates of soil loss for the Adikenafiz and Gerebmihiz catchments compared to the other two (Table 6.4 and Figure 6.7), which may be attributed to their complex terrain and high network of gullies. Maidelle has a relatively simple linear slope with an elongated shape, which may reduce erosion. Gullies are also not as prominent as they are in the above two sites. These attributes would be the reasons for the relatively low soil loss rate of this catchment. In the case of the Laelaywukro catchment, it appears that the LS factor played greater role in the estimated soil loss rate, overriding the good surface cover/management and low erodibility conditions. This site has the highest LS factor among the four catchments, which increases its natural erosion potential.

The variability of soil loss from catchments is a reflection of the physical attributes of catchments and their existing LUC and management conditions. In this study, it was observed that the variability of model results is higher for the catchments with complex terrain (e.g., Laelaywukro, coefficient of variation (CV) = 47%) than for those with relatively simple terrain (e.g., Maidelle, CV = 18%) catchments. This suggests that the application of a single model to different areas may not be possible, especially if the physical characteristics of the sites are very different. Table 6.4 and Figure 6.7, for instance, show that the erosion models show contrasting predictions of soil loss for the Laelaywukro catchment, whereas they show relative consistency for the other three sites. This may be due to the contrasting attributes of the Laelaywukro catchment (rugged and slopy terrain, low erodibility, good surface cover and conservation measures) with contrasting effects on erosion processes, which may not be properly handled by all the models. The STCI (CV = 52%) and the USPED (CV = 50%) models show relatively high variability compared to the USLE2D for the different catchments. This shows that the two models may better capture the heterogeneity of the catchments that might cause differences in soil loss rates.

The STCI and the USLE2D models, which do not consider deposition, are expected to predict higher soil loss rates than the USPED model. However, only the STCI predicts a higher soil loss rate than the USPED for all sites, while the USLE2D predicts lower than the USPED except for the Laelaywukro catchment. This shows that the USLE2D underestimates soil loss in the studied sites. Its prediction also shows different pattern than the two models in that it estimates the highest soil loss (Laelaywukro) for the site with lowest erosion potential based on field evidence and reservoir sediment deposition data. The USPED model, which also considers soil loss due to rill/ephemeral gullies, predicted both erosion and deposition at different positions of the catchments. The soil loss estimate by the USPED also appears to conform to the reality of the catchments, as it predicts high soil loss rate for catchments with steep slopes, poor surface cover and dense network of gullies.

Generally, the magnitude of erosion predicted by the USPED model is higher than that of deposition. For example, for the Adikenafiz catchment, the USPED shows that 62% and 27% of the catchment are characterized by erosion and deposition, respectively, while for Maidelle it shows 56% and 23%. This means that the intensity of soil loss is higher than the amount that can be redistributed within the catchments. This increases the rate of reservoir siltation as most of the sediment detached has higher probability of downstream delivery. However, there appear to be some very high soil loss values along gullies and steep slopes compared to depositions along depressions, which could affect the true balance of soil redistribution within the catchments.

The gross soil loss rates reported in Table 6.4 for the STCI and the USLE2D models do not consider possible deposition and can not represent net soil loss from the catchments. Since the two models do not consider intermediate redistributions, the percentage gross soil loss from catchments that may be delivered to outlets cannot be known. In order to account for such problems, sediment delivery ratio (SDR) estimations were made using equations 6.14 and 6.15 (Table 6.5).

The SDR values calculated using equations 6.14 and 6.15, are fairly consistent for the Adikenafiz and Gerebmihiz catchments, but they are quite different for the other two. The SDR estimates by equation 6.14 are generally lower for most catchments for the STCI model whereas they are higher for the USLE2D model. This could be due to overprediction of soil loss by the STCI model and underprediction by the USLE2D model. The SDR value for the Gerebmihiz catchment based on equation 6.14 and the STCI model seems to be underestimated in relation to the dense network of gullies and pronounced erosion processes observed in this catchment. This may be because of some extreme values that overpredicted the mean soil loss rate affecting the denominator of equation 6.14. When the extreme values of STCI of more than 500 t ha^{-1} y^{-1} are excluded and SDR calculated based on equation 6.14, the mean SDR values increase to around 0.80 and 0.70 for the Adikenafiz and Gerebmihiz catchments, respectively. These values are closer to those estimated using equation 6.15.

The SDR estimates using equation 6.14 and the USLE2D model give values of more than 100% for most of the catchments. This shows that the material that is actually delivered to the outlets is more than that which has been eroded from the respective catchments. This may occur in cases where the majority of the soil loss is from gullies and nearby floodplains (e.g., Walling and Webb, 1996). This could be the case for some of the sites (Adikenafiz and Gerebmihiz), but not for the predominantly gently sloping Maidelle catchment with less prominent gullies. A possible reason could thus be that the USLE2D underpredicted soil loss for some of the catchments.

Table 6.5: SDR for the STCI and USLE2D models based on equations 6.14 and 6.15

Site	STCI	USLE2D	SSY	STCIssy	USLE2Dssy	SDRunit
Adikenafiz	82.5	41.6	49.0	0.60	1.18	0.84
Gerebmihiz	74.6	35.7	39.0	0.52	1.10	0.76
Laelaywukro	30.2	40.0	6.5	0.22	0.16	0.65
Maidelle	29.5	20.6	23.7	0.80	1.15	0.30

STCIssy and USLE2Dssy = SDR (%) values estimated based on equations 6.14. SDRunit = SDR (%) calculated for each hydrological unit using equation 6.15 (the average of all subunits is given here); SSY = area specific sediment yield, t ha^{-1} y^{-1}. STCI and USLE2D are in t ha^{-1} y^{-1}.

The SDR values based on equation 6.15 seem to be slightly underestimated for Maidelle and highly overestimated for Laelaywukro which could be mainly due to differences in terrain complexity. Since equation 6.15 considers height differences (HD) and stream length (SL) of subunits, the SDR values could be underestimated for catchments with less pronounced terrain and elongated shape (Maidelle) and overestimated for those with pronounced terrain and relatively compact shape (Laelaywukro). Field evidence shows that Laelaywukro should have a much lower SDR value than estimated using equation 6.15, because of its good surface cover and an abrupt slope change around the reservoir which can encourage deposition due to rapid loss of kinetic energy of flowing water. Generally, the SDR estimates show that more than 50% of the soil eroded upslope could be delivered to the reservoirs, except for the Laelaywukro catchment (Figure 6.7). This indicates the significance of increasing on-site soil loss on the off-site sedimentation of reservoirs.

Considering the nature of the catchments, the SDR estimates using equation 6.15 are closer to the reality except that it is overestimated for Laelaywukro catchment. Since the SDR estimates based on equation 6.15 are calculated for distributed subcatchments units, they can be better estimates than the gross SDR estimated using equation 6.14. Figure 6.7 shows the net soil loss (USPED), gross soil loss (STCI and USLE2D), and estimated net soil loss by STCI (STCIsdr) and USLE2D (USLE2Dsdr) after adjusted for SDR using equation 6.15.

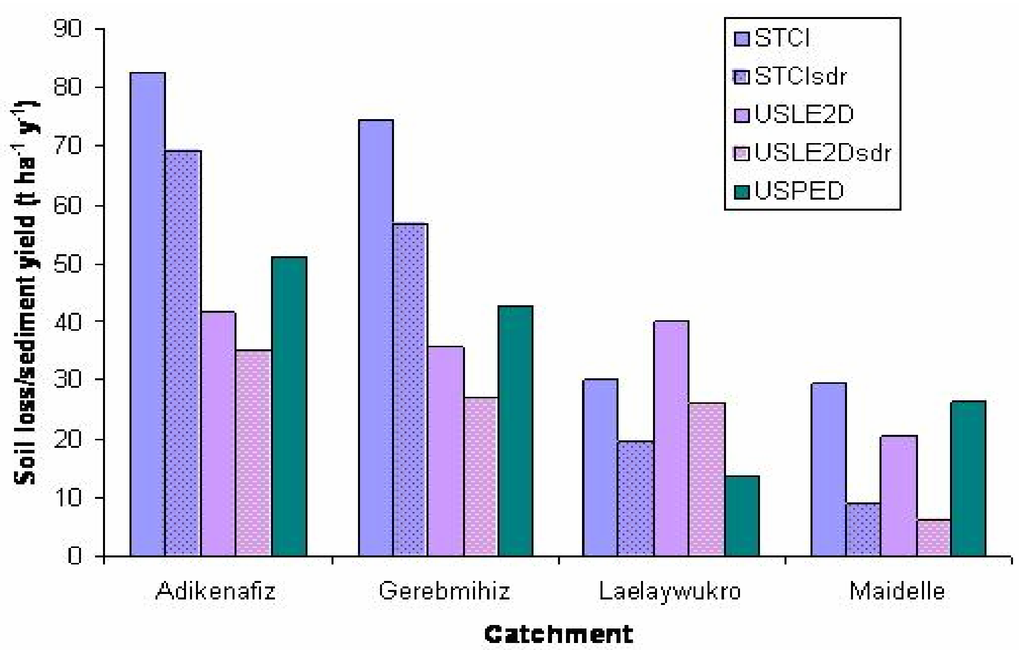
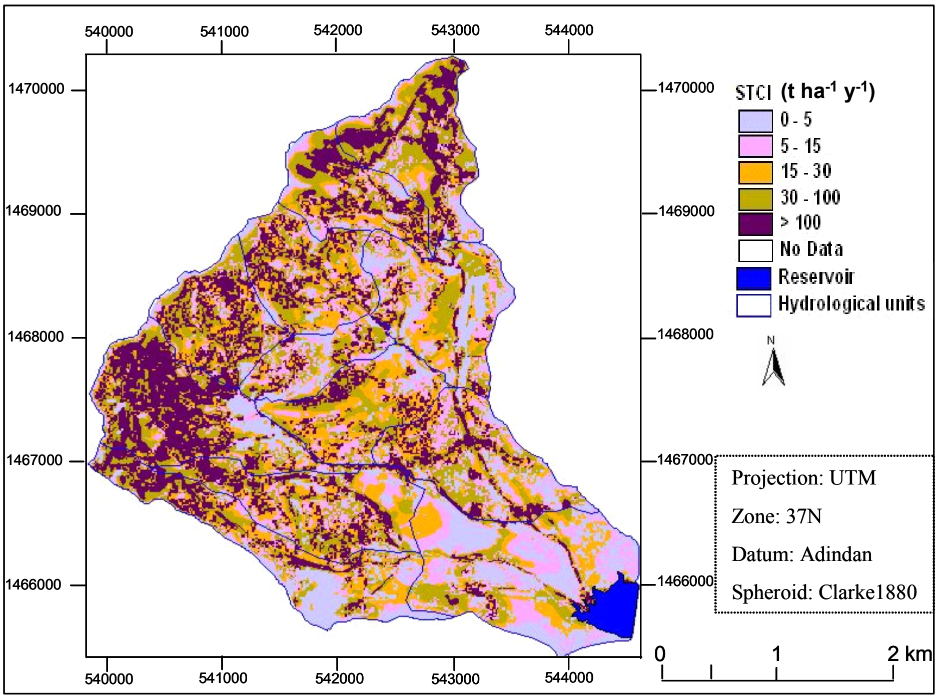


Figure 6.7: Mean annual soil loss rates predicted by the different models and soil loss rates of STCI and USLE2D after adjusted for SDR using equation 6.15 (column 7, Table 6.5) for sites in Tigray, N. Ethiopia

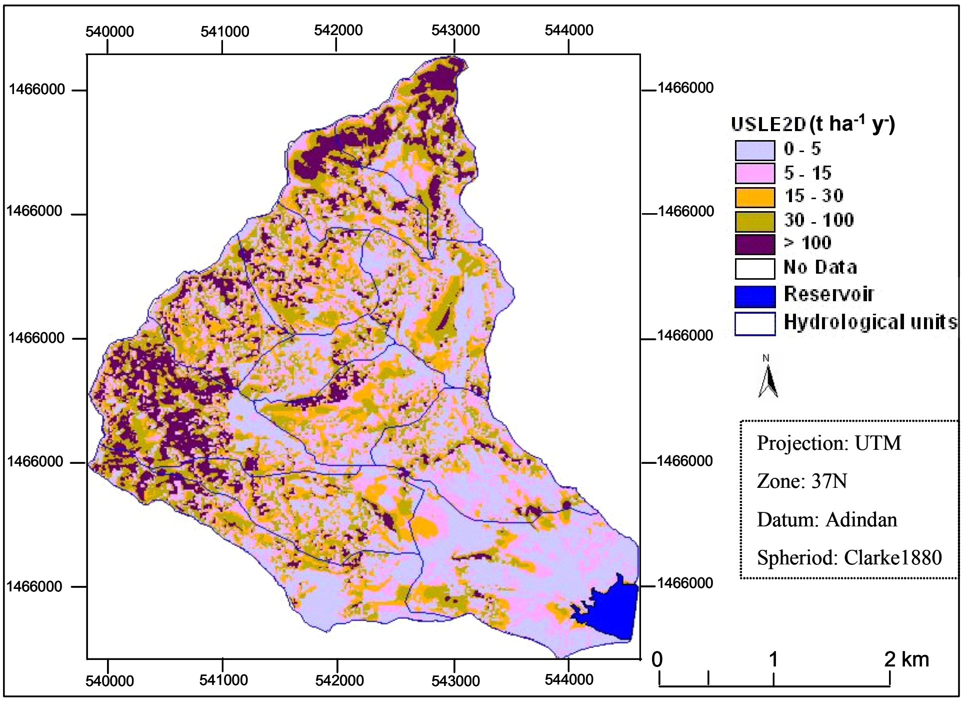
6.7.2 Spatial patterns of erosion/deposition

In developing land management plans and designing appropriate anti-erosion measures at the most relevant locations, it may not always be necessary to precisely quantify soil loss rates and volumes (Vertessy et al., 1990; Reid and Dunne, 1996). Takken et al. (1999) and Jetten et al. (2003) indicate that accurate prediction of the spatial pattern of erosion/deposition is more important for designing erosion control measures than accurate prediction of the amount of runoff and sediment production. Accurate estimation of soil loss rates may also not be possible using the available soil erosion models due to problems in acquiring accurate spatially distributed data, especially at a catchment scale (Van Rompaey et al., 1999; Jetten et al., 2003) and due to the intrinsic problems within the models (Mitasova et al., 2001). Thus, it is more beneficial to identify potential erosion risk areas that may contribute high amounts of sediment to the downstream reservoirs.

Figure 6.8 shows the spatial patterns of erosion and erosion/deposition predicted by the models applied in this study. The legends for the STCI and USLE2D maps reflect five erosion severity classes partly based on FAO/UNDP (1984), whereas the USPED has eight classes to reflect erosion and deposition with negative values showing erosion and positive values showing deposition. Visually, the spatial pattern of soil loss is better revealed by the STCI and USLE2D models than for the USPED, mainly because the latter shows some extreme values of erosion and deposition nearby gullies/streams. Field observation and soil profile data show that the rapid change from erosion to deposition within a short distance is mainly due to changes in slope. While the steep sides of gullies have very high erosion rates, the floors of gullies have very high deposition rates, resulting in maps of "wavy" appearance in the case of the USPED. Careful reclassification of the resulting maps is necessary to obtain meaningful and visually interpretable maps.

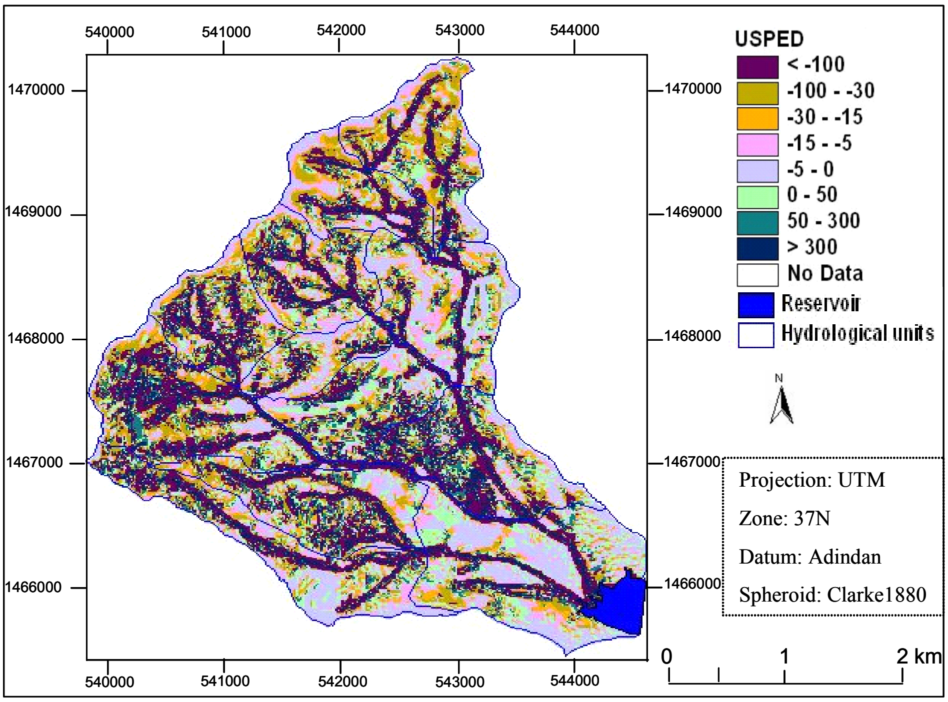


(a)



(b)

Figure 6.8: Spatial patterns of erosion and erosion/deposition for two example catchments: Adikenafiz (a = STCI, b = USLE2D, c = USPED, d = SERPU) and Gerebmihiz (e = STCI, f = USLE2D, g = USPED, h = SERPU). Note that soil loss rates of the STCI and USLE2D are adjusted for SDR using equation 6.15. Negative values show erosion and positive values show deposition (USPED)



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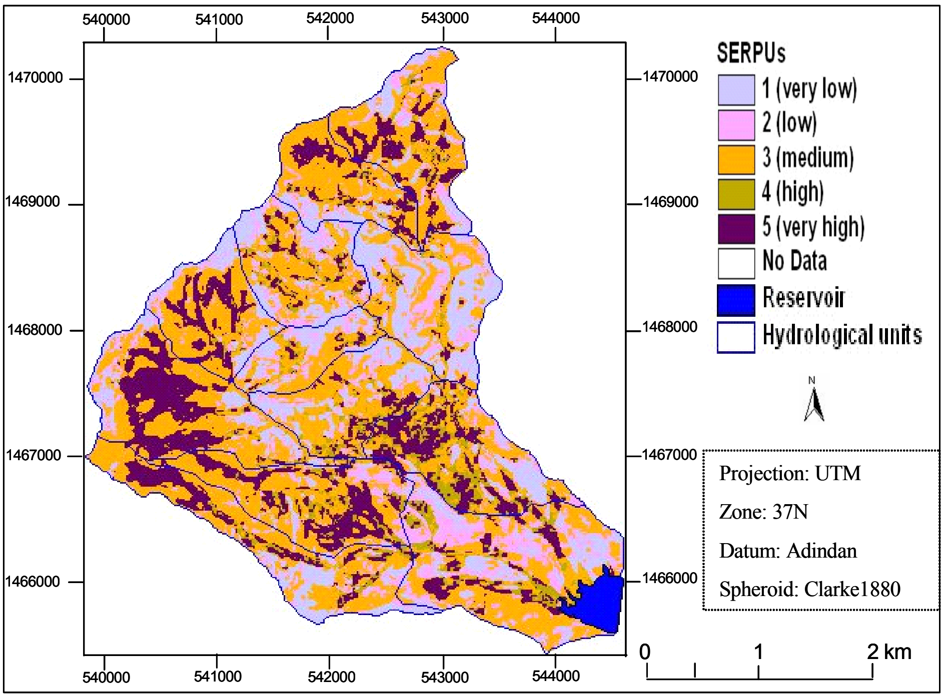
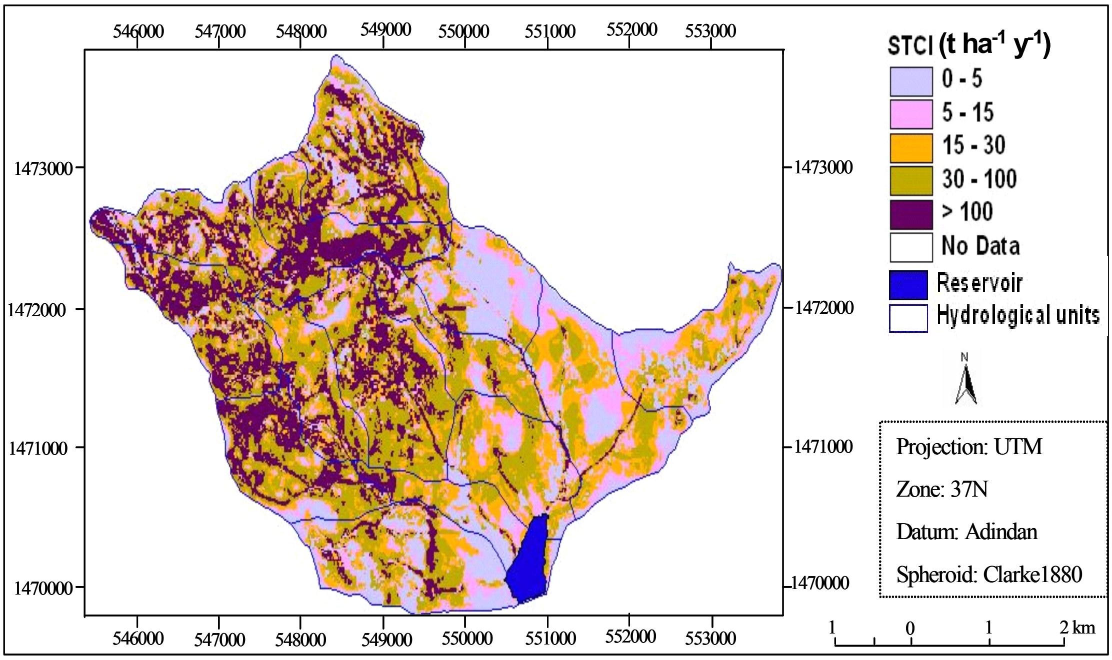
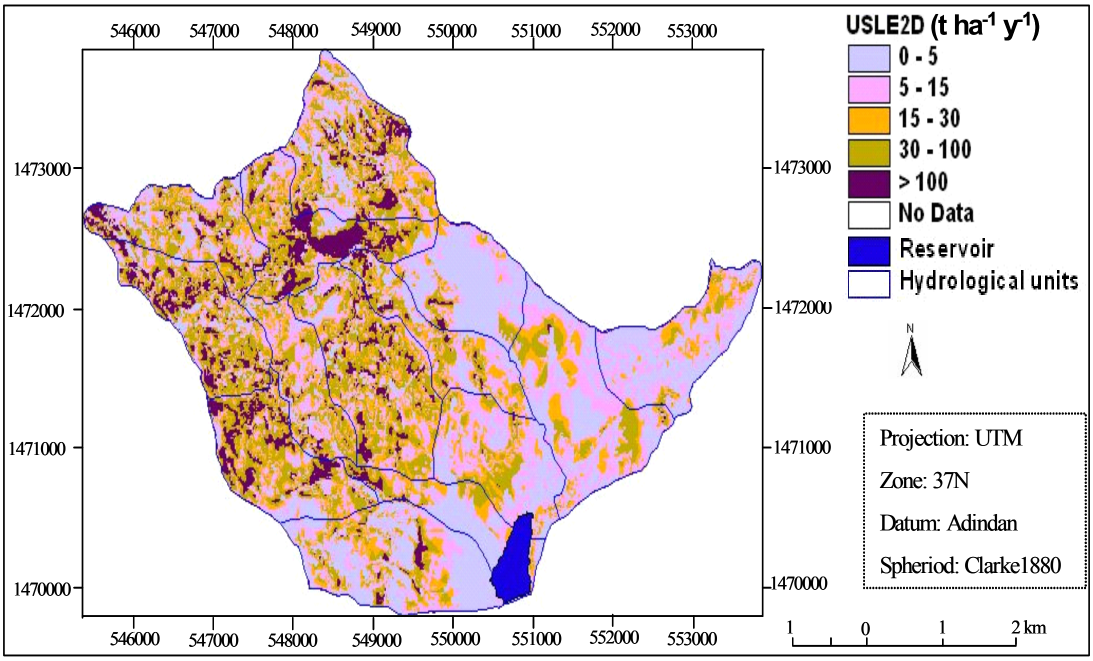


(d)

Figure 6.8: continued

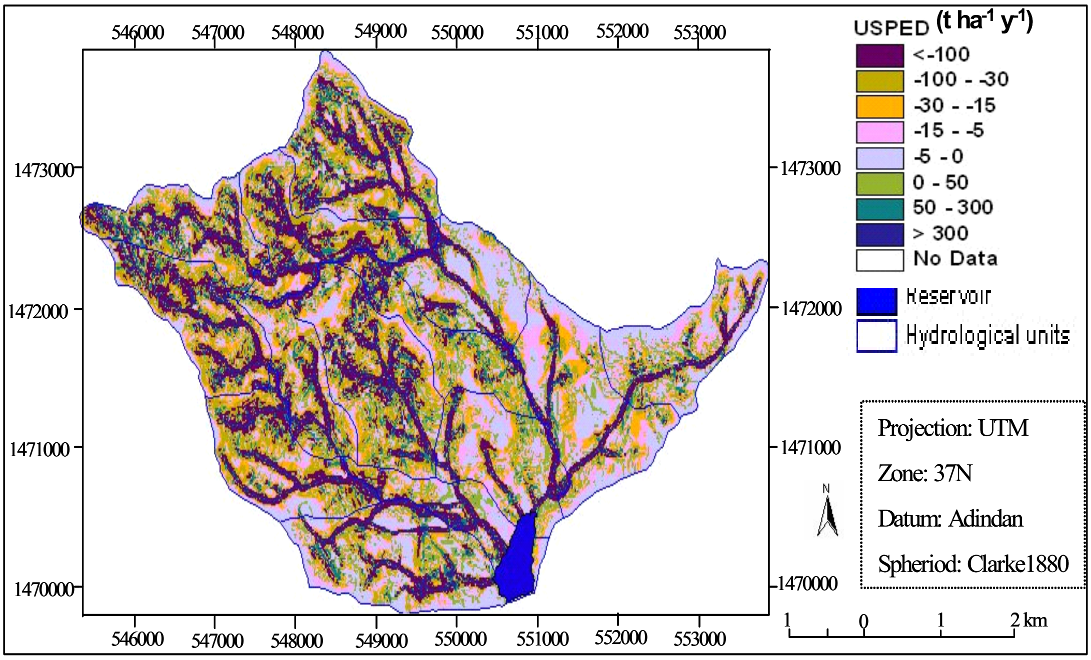


(e)

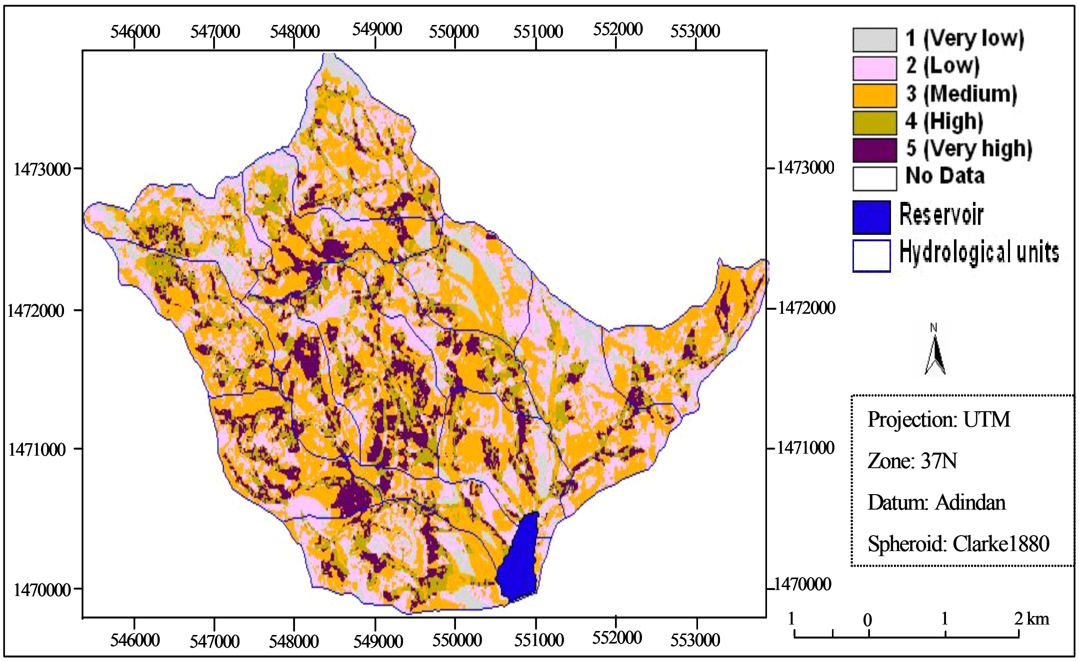


(f)

Figure 6.8: continued



(g)



(h)

Figure 6.8: continued

Generally, all the maps (Figure 6.8) show similar patterns of erosion, such that higher elevation and steep-slope areas with poor surface cover and erodible lithology are more vulnerable to accelerated erosion compared to the lower slope areas of similar cover and lithologic attributes. For most of the catchments, the landscape positions where erosion is above the tolerable limit are located on the upslopes, where slopes are generally greater than 15°. On the other hand, the landscape positions where soil loss is within the tolerable limit and therefore with relatively low sediment yield potential are usually on slopes less than 8°. However, the widespread and collapsing gullies, which can contribute a great deal of sediment, are located in the downstream positions of catchments, where the slopes are not very steep. This is well represented by the USPED model, which predicts high soil loss rates along gullies and topographic swales.

The patterns of erosion/deposition (Figure 6.8) strongly reflect the terrain configuration of the catchments in that high erosion areas occur along the main drainage lines and shoulder positions, which also correspond with observed gully and rill erosion. The high soil loss rates following drainage lines and along shoulder positions and the lower ones on summits reflect the effect of catchment convergence and divergence, respectively (Mitasova et al., 1997). On the other hand, high rates of deposition (USPED) are observed on the lower positions of the catchments where slopes are low. The highest deposition sites are at the central points of drainage lines immediately below the zones of high erosion. Similar observations were reported in a study by Mitasova et al. (2001).

One of the achievements of the models, mainly the USPED and STCI to some extent, is that they managed to reveal the spatial patterns of gullies within catchments, which confirm well with evidence in the field. Previous chapters and other sources also show the significance of gullies in contributing to sedimentation of reservoirs either through efficient delivery of sediments (Poesen et al., 2003) or by contributing sediment themselves due mainly to floodplain erosion and bank collapse (Walling and Webb, 1996; Trimble, 1995). A study by Shibru et al. (2003) in eastern Ethiopia, for instance, estimated a soil loss rate of about 25 t ha^{-1} y^{-1} from gullies alone.

6.8 Evaluation of model results

6.8.1 Results of models related to sediment yield to reservoirs

The rate of reservoir sediment deposition may be used to assess model results with the assumption that, over longer time periods, there is a connection between sedimentation in reservoirs and erosion in the contributing catchments (Morris and Fan, 1998). In this study, the sediment yield estimates made for the four reservoir catchments (Chapter 4) were compared with soil loss rates predicted by the three erosion models (Figure 6.9).

From Figure 6.9, it can be seen that the soil loss estimated by the USPED model shows the best agreement to what is accumulated in the reservoirs for all catchments (Pearson's $r > 0.97$, at 0.01). The soil loss rates predicted by the USPED model are consistently but slightly higher than estimated reservoir depositions. The higher soil loss prediction by the model compared to sediment yield data could be attributed to the higher soil loss estimates at gullies and topographic hollows than the amount of deposition it predicts for those sites.

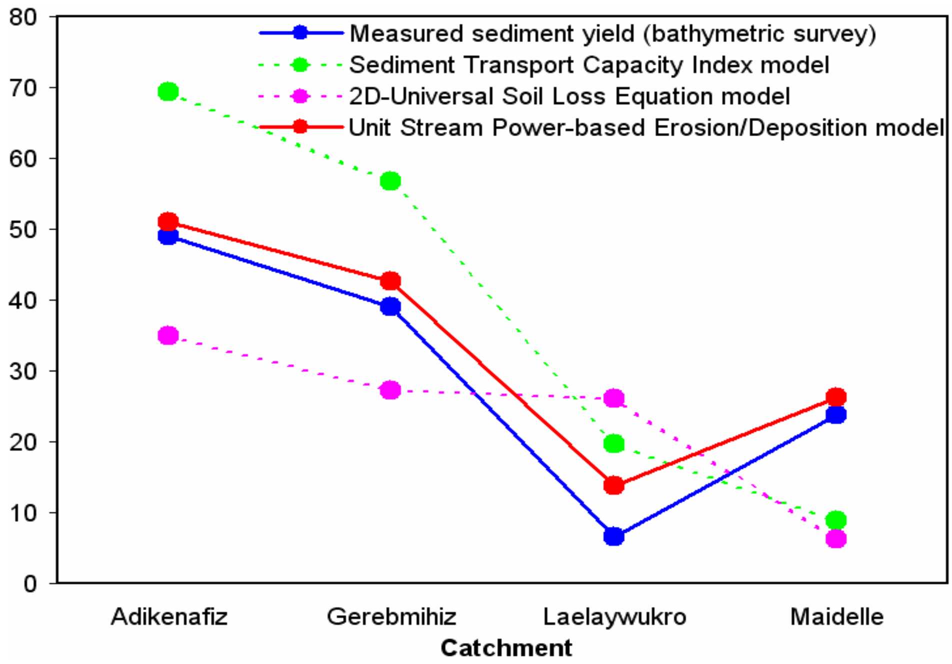


Figure 6.9: Relationship between reservoir-based sediment yield estimates and model-based soil erosion predictions in Tigray, N. Ethiopia. Soil loss predictions by STCI and USLE2D models are adjusted for SDR using equation 6.15

The STCI shows similar pattern to the SSY and its correlation with SSY is stronger (r = 0.86, though not significant) than that of USLE2D and SSY. The USLE2D shows relatively lower and non significant correlation (r = 0.44) between what is eroded from catchments with what ends up in the reservoirs. The main reason for the low correlation between USLE2D and reservoir deposition could be the fact that it highly overestimated soil loss for Laelaywukro catchment and underestimated for the others, opposite to the pattern observed in the SSY. The model also predicts lower soil loss rate than what is actually deposited in reservoirs, which may not conform the reality as the model does not consider intermediate depositions.

The above trends are reflection of pattern and may not show differences in the magnitude of errors of the model estimations. To identify the model which shows the best fit to the observed data (SSY), the square root of mean square error (SMSE) and its percentage were calculated. Based on the calculated SMSE, the performance of the models can be rated as the USPED being the best followed by the USLE2D and STCI. The over all error of the USPED model was about 4 t ha^{-1} y^{-1} (about 14% of the mean value of the observed sediment deposition) which can be considered acceptable. The USLE2D model has an overall error of 16 t ha^{-1} y^{-1} (about 54% of the observed mean) and that of STCI has an error of about 17 t ha^{-1} y^{-1} (about 56% of the observed mean). According to the Person's correlation and SMSE results, only the USPED model can be acceptable while the other two have higher levels of associated errors and can not be acceptable.

6.8.2 Results of models related to ^{137}Cs data

Table 6.6 shows the results of the ^{137}Cs-based soil redistribution rates based on the Proportional model (PM) and simple Mass Balance Model (MBM1) presented by Walling and He (2001) with a mean ^{137}Cs reference activity of 1615 Bq m^2. The results show that over the ca. 50-year period following the caesium fallouts (1953-2002), net soil loss from the hillslopes based on the PM and MBM1, respectively, averaged between 15 to 24 t ha^{-1} y^{-1} from the erosional areas of the hillslopes, and net deposition onto the depositional areas of the hillslopes averaged between 6 to 10 t ha^{-1} y^{-1}. Average net erosion from the hillslopes was estimated between 9 to 15 t ha^{-1} y^{-1} with an average SDR of 39%.

The hillslopes generally have gentle slopes with uniform topography (minimum curvature) and are cultivated with no significant permanent surface cover. There are no signs of rill or ephemeral gully erosion within the sampled hillslopes (except the gully that crosses the hillslopes), and conservation activities are minimal. The main reason for soil loss could be surface erosion due to absence of surface cover and repeated cultivation. Tillage translocation could also contribute to soil redistribution within the hillslopes. Considering that the ^{137}Cs hillslopes have relatively gentle slopes and no rills/gullies as compared to the other parts of the catchment, the lower soil loss estimates using the ^{137}Cs method (9-15 t ha^{-1} y^{-1}) compared to erosion from the whole catchment (Table 6.4) and deposition in the catchment outlet (SSY of 24 t ha^{-1} y^{-1}) may be acceptable. Within a similar environment and similar size hillslopes, Nyssen (1997, 2001) estimated soil loss rates of 7.4 t ha^{-1} y^{-1} and 11.2 t ha^{-1} y^{-1}, respectively.

Table 6.6: Mean soil redistribution rate estimated based on ^{137}Cs data using the PM and MBM1 (Walling and He, 2001) for converging hillslopes in the Maidelle catchment, Tigray, N. Ethiopia

	Mean erosion		**Mean deposition**		**Net soil loss**		**Total sediment delivery ratio**	
Transect	PM	MBM1	PM	MBM1	PM	MBM1	PM	MBM1
1	-9.6	-17.4	7.7	11.1	-2.0	-6.3	0.8	0.8
2	-18.8	-30.0	7.9	13.1	-11.0	-17.0	0.4	0.4
3	-16.7	-25.7	2.6	4.1	-4.4	-21.6	0.9	0.9
4	-4.7	-6.1	9.3	12.6	+5.0	+6.5	0.3	0.3
5	-14.5	-23.0	8.5	12.0	-6.0	-11.0	0.8	0.8
6	-18.2	-32.0	0.0	0.0	-18.0	-32.0	1.0	1.0
7	-21.7	-37.0	8.6	14.7	-13.0	-2.2.2	0.4	0.4
Average	*-14.9*	*-24.4*	*6.4*	*9.7*	*-8.5*	*-14.7*	*0.38*	*0.40*

Note that negative values indicate erosion and positive values indicate deposition.

To assess the agreement between soil redistribution based on ^{137}Cs- and model-based results, the soil loss and deposition rates of each ^{137}Cs sample point were correlated with the results of soil erosion and erosion/deposition of corresponding sample points predicted by the models (Figure 6.10). Since the STCI and USLE2D do not take into account deposition processes, only eroding sites were identified and correlated with the ^{137}Cs data. The gross soil loss estimates by the STCI and USLE2D were also adjusted using the ^{137}Cs-based SDR estimate (0.39, Table 6.6) for the hillslopes before the correlation.

Figure 6.10 shows that the USPED model results are better correlated with the ^{137}Cs soil redistribution rates of each ^{137}Cs sample point. The results of this model are significantly correlated (r = 0.40) and (r = 0.36) for the PM and MBM1 results, respectively, at 5% significant level. The correlation is not very strong mainly due to some extreme values predicted by the model around gully edges. In addition, the mode predicted soil loss for areas of ^{137}Cs gains and vice-versa in 6 cases. As can be seen in Figure 6.10, the STCI and USLE2D model results are poorly correlated with ^{137}Cs results. This may be mainly because the two models do not predict deposition and correlating with only eroding sites of ^{137}Cs may limit their agreement as the number of points considered reduced.

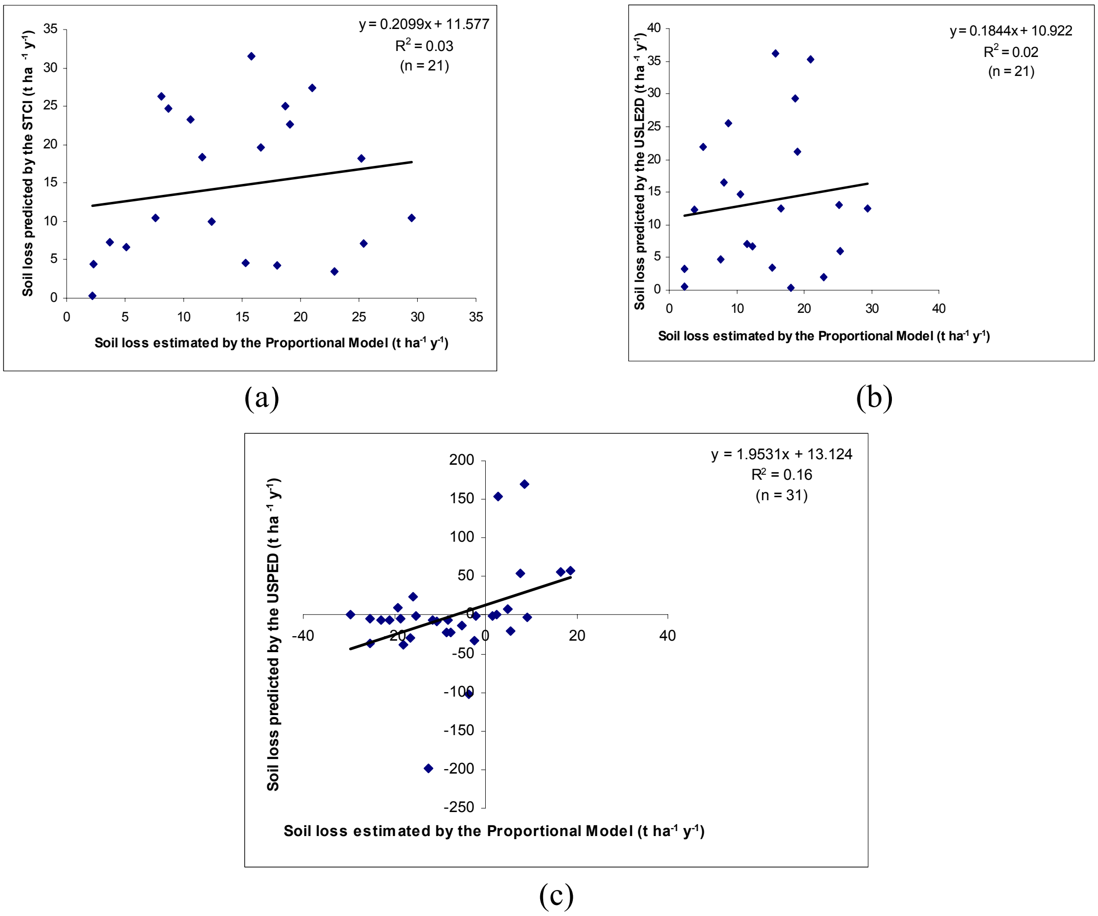


Figure 6.10: Scatter plot representing the relationship between ^{137}Cs-estimated soil redistribution rates (based on the PM model of Walling and He, 2001) with those predicted by the models (a) STCI, (b) USLE2D, and (c) USPED. STCI and USLE2D values are adjusted using SDR of hillslopes (Table 6.6.)

The comparison of ^{137}Cs-estimated and model-predicted erosion/deposition values of each sample point (e.g., Figure 6.10) could indicate the overall agreement between the two. It, however, does not show the agreements in predicting the spatial variation of soil redistribution. To evaluate correspondence between the spatial pattern of erosion/deposition using the models and the ^{137}Cs-based soil redistribution patterns, the ^{137}Cs data were interpolated to derive soil redistribution map for the hillslopes (Chappell et al., 1998; Walling et al., 2003). Figure 6.11 shows the the spatial pattern of soil redistribution as estimated by the three models and the ^{137}Cs data for the hillslopes.

The soil loss rates of the hillslopes (interpolated maps) was about 6 t ha^{-1} y^{-1}, while soil loss for the same areas based on the models ranges from 29 - 44 t ha^{-1} y^{-1} (about 6 times higher than the ^{137}Cs results). When the extreme values by the USPED (mainly around the gully) are adjusted to a value of a little higher than the local highs and the gross estimates by the STCI and USLE2D are adjusted for SDR, the estimate reduces to 4 – 17 t ha^{-1} y^{-1}. This is in good agreement with the ^{137}Cs based estimate since ^{137}Cs samples were not collected from the gully that crosses the hillslopes.

Figure 6.11a shows that ^{137}Cs loss is higher on the middle part of the south-west facing hillslope and the upper side of the north-east facing hillslope as well as at isolated sites near the gully. ^{137}Cs deposition is higher on the lower slope positions following the gully. ^{137}Cs loss at the central-western edge of the south-west facing hillslope is comparatively higher than at the other parts, which could be due to increased erosion caused by the slightly inclined surface. The north-east facing hillslope shows a higher soil loss mainly due to the short slope length and steep gradient, which would result in accelerated flow and reduced travel time.

When patterns of erosion and erosion/deposition predicted by the models were compared with the ^{137}Cs maps (Figure 6.11), similarity between the maps is generally poor. The poor spatial pattern agreement between the STCI and USLE2D models with ^{137}Cs-based soil redistribution maps was expected, as the models do not predict deposition caused by local changes in slope, shape or management practices. The USPED model shows a roughly similar pattern to the ^{137}Cs-based results, since it models deposition. The best agreements are on depositional sites around the gully and on the hillslope crest where erosion is minimum.

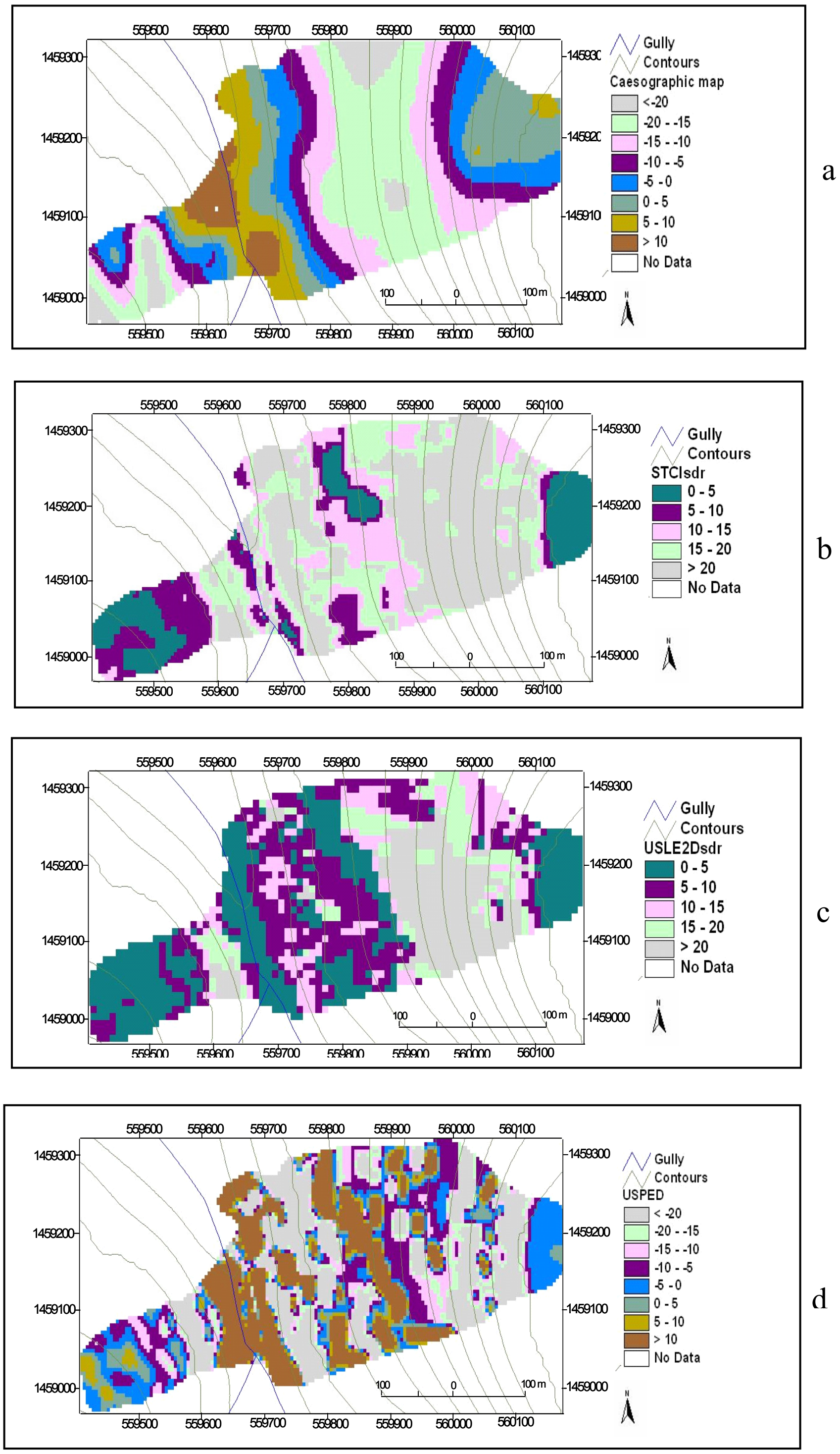


Figure 6.11: Spatial redistribution of soil loss (a) caesographic map (PM model) (b) STCI, (c) USLE2D, (d) USPED for hillslopes of Maidelle catchment in Tigray, N. Ethiopia. Extreme soil losses estimated by the USPED along gully were adjusted to be a little higher than the local values obtained by the model. The STCI and USLE2D were adjusted for SDR (Table 6.6). Negative values show erosion while positive values show deposition (^{137}Cs and USPED)

Generally, the spatial patterns of erosion/deposition represented by the models for the hillslopes do not conform very well to those based on ^{137}Cs data. One of the reasons could be that the number of points used for the interpolation was not similar. For instance, Figure 6.11d shows that there is a rapid change from erosion to deposition or in values of each pixel for the USPED model compared to the ^{137}Cs-based results (Figure 6.11a). This could be due to differences in the detail of spatial representation (only 31 points of ^{137}Cs data compared to over 1700 points representing USPED data for the hillslopes). The USPED model also predicted high deposition on depressions/hollows and high erosion on shoulders and valley sides (ridges). The erosion/deposition rates at these same locations, however, are not as extreme when estimated based on ^{137}Cs resulting in lower agreements. Other processes that could lead to soil redistribution such as tillage translocation could also create differences (e.g., Nearing, 2000). The different time scales associated with the model predictions (long-term average soil erosion rates derived from ^{137}Cs measurements in relation to short-term soil erosion prediction by models) could also cause discrepancies, though the effect on spatial patterns may not be as such significant (Walling and He, 2003).

In order to account for the spatial variation of ^{137}Cs and thus variation in soil redistribution, large sets of data will be required on ^{137}Cs inventories (Sutherland, 1994; Chappell et al., 1998). If the number of ^{137}Cs points measured is small (31 in this study), the potential to account for spatial variability would be minimal and comparison with maps interpolated from a large datasets may create discrepancies.

In order to evaluate the possible impact of differences in the number of data points between the model-based and ^{137}Cs-based results, model estimates for the 31 ^{137}Cs sample locations were selected and interpolated. This enables the spatial pattern maps of the three models to be based on same number of points and locations. When the interpolated maps are compared, the correlation between the spatial pattern of soil redistribution based on models and ^{137}Cs maps improves slightly, mainly for the USPED (Figure 6.12). Figures 6.12a and b show similar pattern of soil redistribution, mainly around the gully, northeast facing hillslope and central and western sections of the southwest facing hillslope. For the STCI and USLE2D models, the results were not better than those shown in Figure 6.11 and are not shown in Figure 6.12.

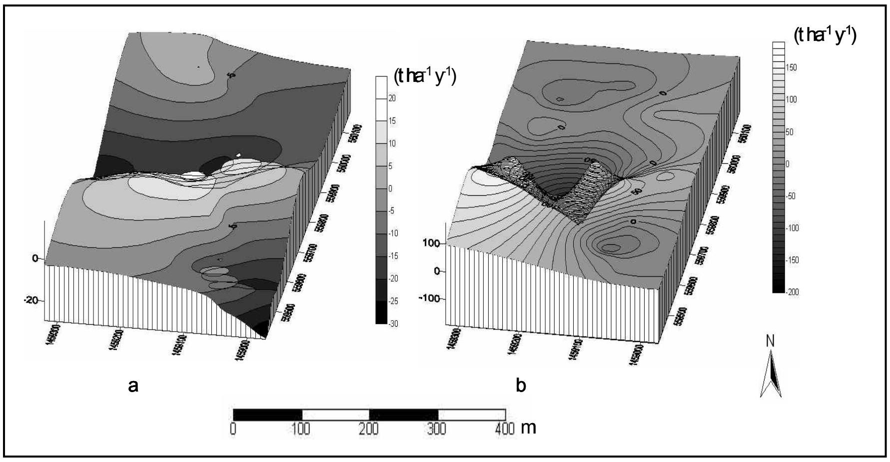


Figure 6.12: Spatial patterns of soil redistribution represented by (a) caesographic map, (b) USPED model interpolated based on 31 points (extracted from the corresponding ^{137}Cs points) for the hillslopes in Maidelle catchment, Tigray, N. Ethiopia

6.8.3 Results of models related to soil profile data

The soil erosion and erosion/deposition rates predicted by the models were compared with measured soil profile depth data for selected catchments. The USPED model was evaluated to see if it identifies areas of erosion and deposition consistent with soil profile truncation and buried soil, respectively. The STCI and USLE2D were assessed in terms of their capacity to identify areas of soil truncation and/or do not predict high erosion on areas where buried soils and/or alluvial/colluvial deposits are observed.

Table 6.7 summarizes the relation between soil profile data and model-based soil erosion/deposition predictions for the Gerebmihiz catchment. The USPED model predicts erosion and deposition in about 70% and 50% of the pits, respectively. In most cases, at sites where truncated soil profile was observed, the model estimated high soil loss rate (more than 20 t ha^{-1} y^{-1}) while at locations of buried soil or colluvial/alluvial deposit, the model predicted deposition of more than 10 t ha^{-1} y^{-1}. The STCI and USLE2D models predicted soil loss rates of more than 20 t ha^{-1} y^{-1} in most areas characterized by truncated soils while they predicted less than 8 t ha^{-1} y^{-1} in most areas of colluvial/alluvial deposit and buried soils. The fact that the two models predicted erosion at deposition sites means that their strict application may require exclusion of depositional sites (e.g., Mitasova et al., 2001).

While the USPED properly identifies eroding and depositional sites, the STCI and USLE2D identify eroding sites only, which is also expected as the models do not predict deposition. In relation to sites of colluvial/alluvial deposit and/or buried soils (6 sites), the two models predicted lower rate of soil loss for 4 sites with 2 sites predicted to have high soil loss rate of more than 25 t ha^{-1} y^{-1}. The USPED thus can be considered better than the STCI and USLE2D models as it also predicts sites of deposition at the same time performing equally in identifying stable and eroding sites.

Table 6.7: Relation between soil profile data and model results for Gerebmihiz catchment in Tigray, N. Ethiopia.

Site status	**Number of pits observed**	**Proportion accurately predicted**		
		STCI	**USLE2D**	**USPED**
Stable[1]	7	3 (43%)	4 (57%)	4 (57%)
Eroding	15	11 (73%)	10 (67%)	10 (67%)
Aggrading	6	0	0	3 (50%)

[1] Slope is gentle and there is no evidence of soil truncation or deposition, with soil loss and gain some what balanced. When soil loss prediction is within ± 5 t ha^{-1} y^{-1}, it is considered as stable. The soil loss values of STCI and USLE2D are adjusted for SDR using equation 6.15.

Figure 6.13 shows the relationship between model results and soil profile data for a portion of the Gerebmihiz catchment. The figure shows that, the USPED not only captures the spatial variability of erosion/deposition across different landscapes (following the summit-foot slope direction) but also reflects well the differences in erosion/deposition due to surface curvature. In most of the cases, erosion is predicted on the sides of hillslopes, while deposition is predicted in depressions and thalwegs. Eroding piedmont sides and shoulder positions are mostly predicted to show soil loss, while summit and foot slope positions show stability or soil gain. Another significant contribution of the USPED model is that soil loss around gullies and convex backslopes are well captured.

Since the STCI and USLE2D predict only erosion, the dynamics of soil loss over the different positions of the landscape are not very clear. However, they show differences in the amount of soil loss.

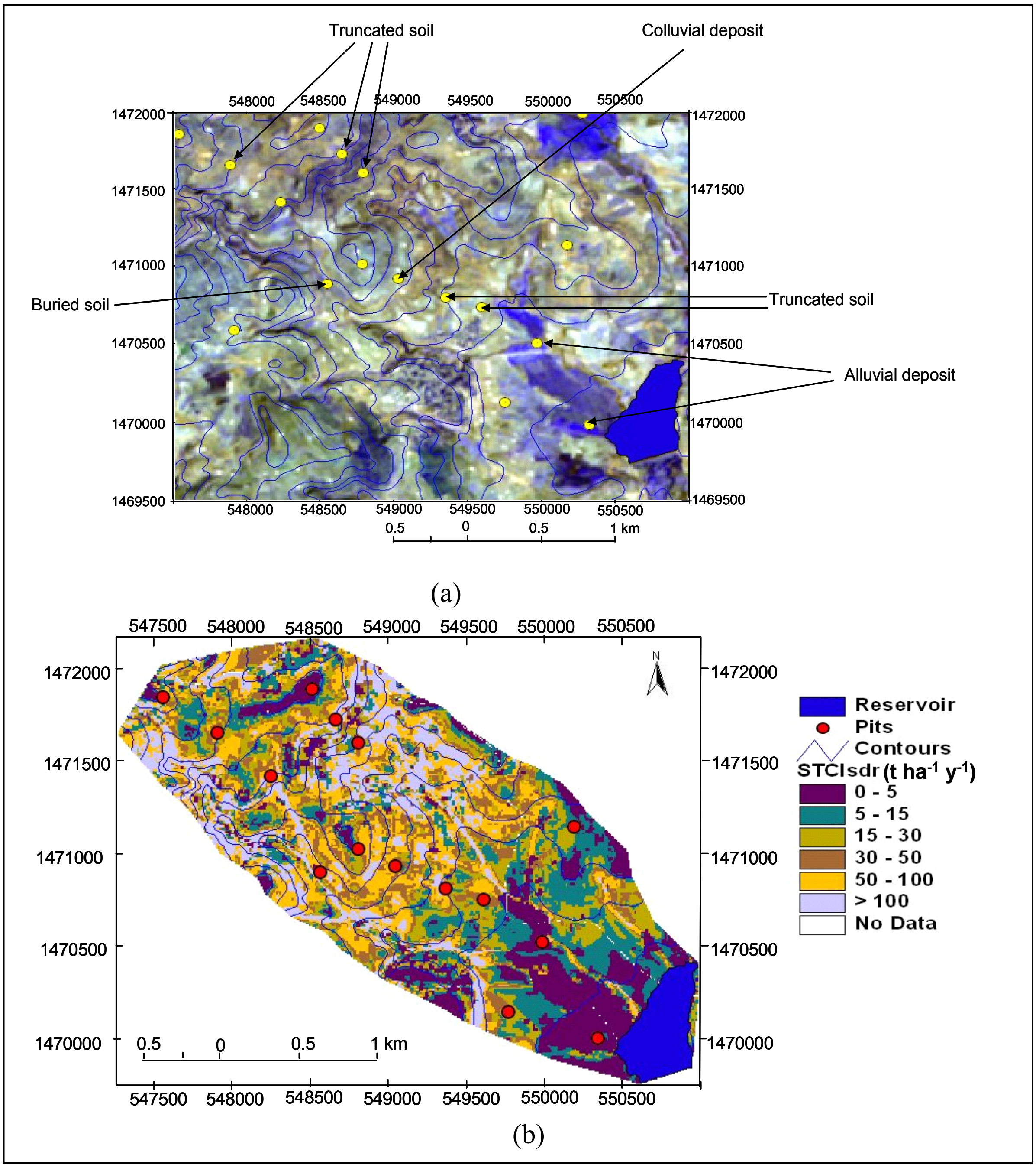


Figure 6.13: (a) Soil profile points and predicted soil erosion/deposition (t ha^{-1} y^{-1}) based on (b) STCI, (c) USLE2D and (d) USPED models for a small sample area of Gerebmihiz catchment in Tigray, N. Ethiopia. The STCIsdr and USLE2Dsdr indicate results adjusted for SDR using equation 6.15. Negative values show erosion and positive ones show deposition (USPED)

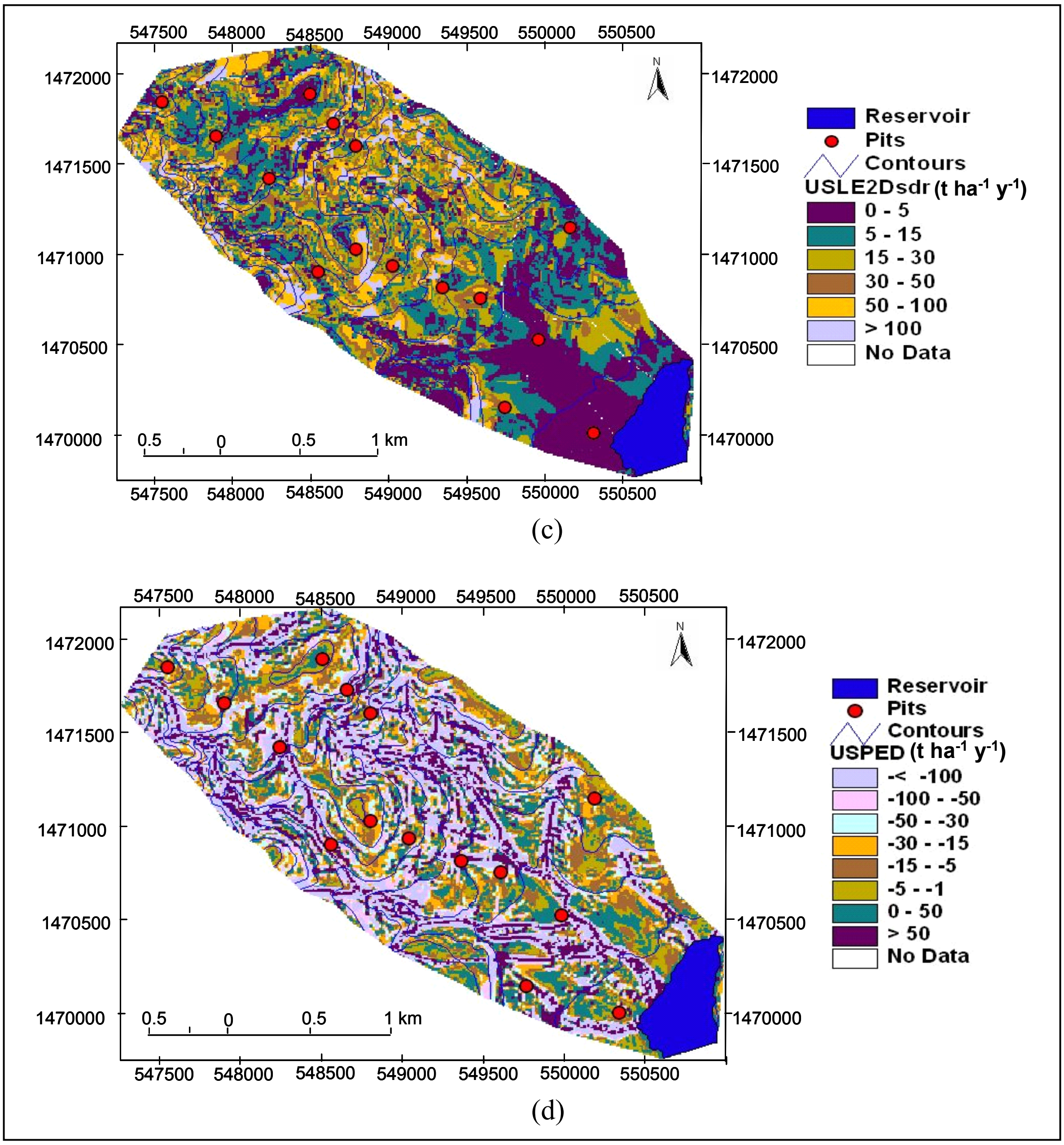


Figure 6.13: continued

Similar approaches applied in the Laelaywukro catchment also show that the USPED model represents the spatial pattern of erosion/deposition better. Out of 11 pits, it shows agreement with 8 (5 of them depositional sites) with most of the disagreements located at the upslope position of the catchment where it predicts slight erosion for sites of very truncated soil profile. The model very well predicted the areas of high alluvial deposition at the lower position of the catchment and high erosion on the areas characterized by rock outcrops.

In both catchments, the USPED shows better agreement with soil profile data than the STCI and USLE2D models. The major disagreement between the USPED model results and the soil profile data is that some areas characterized by highly truncated soils do not have a high soil loss rate if they are located on a relatively level slope such as the summit position. Most of such areas have degraded soil with a dense network of gullies on the backslopes generally increasing from summit divides downwards due to increasing slope gradient. The USPED model captures the dynamics of increasing erosion with downward distance from divides better but does not reflect differences in the proportion of soil loss due to differences in surface cover (mainly in summit positions and flat areas).

6.8.4 Results of models related to the SERPUs

The SERPUs maps and the results of the three models for 2 example catchments are shown in Figure 6.8. Comparison of the maps shows that the spatial patterns of potential zones of high runoff and sediment yield represented in the SERPUs show general agreement with those of erosion models, though there are differences between models. Visually, the USPED model shows more resemblance to the SERPUs of the different catchments followed by STCI and USLE2D. This is mainly because SERPUs reveal the patterns of gully networks and do the USPED model to a large extent and STCI to some extent (Figure 6.8).

In order to be able to quantitatively compare the soil loss prediction by the models with the SERPUs, the results of the models were reclassified into five erosion categories, similar to the SERPUs. The class for each category (Table 6.8) was partially based on FAO/UNDP (1984). Only the eroding areas of the USPED were identified for the comparison, since the SERPUs are more sensitive to potential runoff and erosion processes. The relation between the two maps (model-based and the SERPUs) was then assessed using the coincidence matrix of the Kappa Index (Congalton and Mead, 1983), which enables evaluating the degree of similarity between the two maps (Lillesand and Kiefer, 1994). In order to limit the influence of the classification system and to account for uncertainties in the SERPUs categorization, possible misclassification into one immediate neighboring class (i.e., very low class in the SERPUs predicted as low in the models, and so on) was considered acceptable. To achieve this, weighting factors were introduced such that for neighboring classes, weighs were set to 1 (original distances retained) and for larger disagreements, the weighs that linearly depend on the distance between classes were assigned (Table 6.9) (Vigiak et al., 2005). The Kappa Index of Agreement (KIA) for three of the study sites for which SERPUs are available is shown in Table 6.10.

Table 6.8: Classification of results of erosion models into different categories of soil loss

Soil loss range	Soil loss class	Category
0-5	1	Very low
5 – 15	2	Low
15 – 30	3	Medium
30 - 50	4	High
> 50	5	Very high

Table 6.10 illustrates that all models show about an almost equal level of similarity with the SERPUs. The models show better agreement with the SERPUs for the lower and higher erosion categories than for the middle ones, thus are capable to properly identify the areas with the lowest and highest possibility of erosion and sediment yield risk. The areas where the SERPU classes and model-based results predict high soil loss should be considered areas requiring better management. Based on this, high elevation (steep slope) positions and topographic swales and gullies should be given priority of conservation.

Table 6.9: Kappa coefficient weights for the different categories of erosion

	Very low (1)	Low (2)	Medium (3)	High (4)	Very high (5)
Very low (1)	1	1	0.5	0.25	0
Low (2)	1	1	1	0.5	0.25
Medium (3)	0.5	1	1	1	0.5
High (4)	0.25	0.5	1	1	1
Very high (5)	0	0.25	0.5	1	1

The agreement between models and SERPUs is not high, except the very low and very high soil loss categories. This may be due to problems in the ranges of soil losses used in each erosion class. The middle category shows the poorest correlation which may be due to problem during ranking factors. It is generally easier to assign accurate ranks for extreme values than medium ones which may affect the quality of the SERPUs. The assumption of linear relationship between factors and assigning equal weight to each class of the different factors may also have an effect. Proper calibration of the SERPU classes with respect to their behavior on erosion and assigning weighing factors to each class could give them more “physical meaning”, which might improve their correlation with model results (Kirkby, 1999; Kosmas et al., 1999).

Table 6.10: Kappa Index of Agreement (KIA) between predicted model results and SERPUs of three catchments in Tigray, N. Ethiopia.

Category	Kappa Index of Agreement (KIA)								
	Adikenafiz			**Gerebmihiz**			**Maidelle**		
	STCI	**USLE2D**	**USPED**	**STCI**	**USLE2D**	**USPED**	**STCI**	**USLE2D**	**USPED**
1	*0.47*	*0.49*	*0.49*	*0.49*	*0.52*	*0.49*	*0.53*	*0.53*	*0.50*
2	0.12	0.13	0.16	0.10	0.12	0.14	0.12	0.12	0.04
3	0.07	0.05	0.05	0.09	0.07	0.05	0.10	0.10	0.09
4	0.14	0.11	0.15	0.11	0.13	0.18	0.16	0.07	0.04
5	*0.48*	*0.47*	*0.54*	*0.52*	*0.58*	*0.53*	*0.54*	*0.51*	*0.45*

Italic values show that the low and high erosion categories of the SERPUs correspond well with similar categories of soil loss as predicted by soil erosion models.

Generally, the SERPUs can be helpful so as to identify erosion sensitive areas provided that some basic information on terrain, LUC, lithology, and gullies are available. The advantage of the SERPUs could be that they do not demand complicated data and they can be used to locate areas more vulnerable to erosion and therefore require prior management planning. In this study, the SERPUs show slightly better agreement with the USPED models and more so for the Adikenafiz and Gerebmihiz catchments compared to the Maidelle catchment. In fact, all the three models show relatively better agreement with the SERPUs for the Adikenafiz and Gerebmihiz catchments than the case of Maidelle catchment. The main reason could be that the catchment has generally “uniform” attributes such as shale dominated lithology, poor surface cover and gentle slope, which make it difficult to assign distinct ranks to these factors when creating the SERPUs. In such circumstances, detailed field visit will be required to properly calibrate the SERPUs.

6.8.5 Results of models related to field-based erosion sensitivity scores

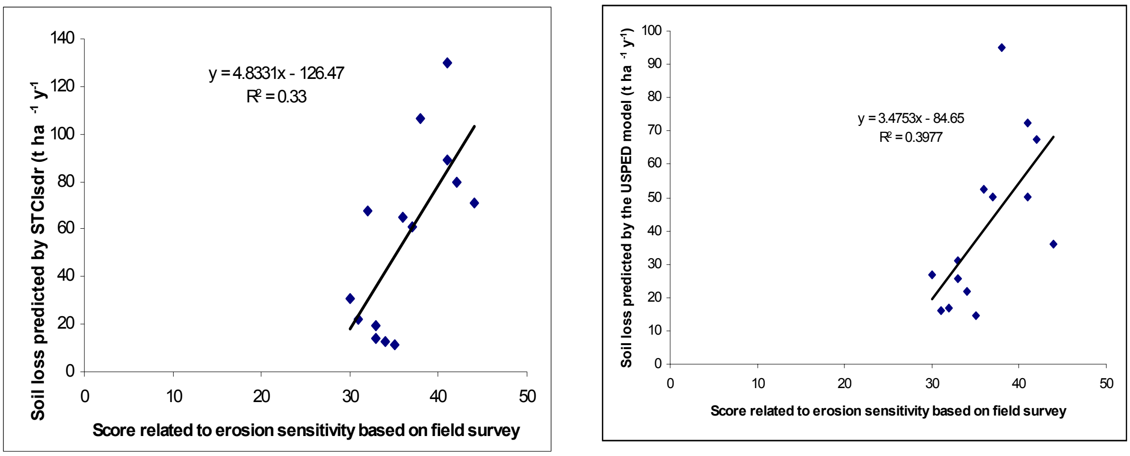
Table 6.11 shows the results of the correlation between the field-based erosion sensitivity scores and the model results for each catchment and subunit. The table shows that the agreement between the field-based assessment of soil loss and sediment delivery potential of catchments based on geomorphic evidences and model results is roughly similar for all models. All models show better performance for the Adikenafiz and Gerebmihiz catchments whereas they perform poorly for the other two sites. The STCI and USLE2D performed poorly for Laelaywukro (most complex catchment) and the USPED performed poorly for Maidelle (relatively simple terrain catchment). The fact that the model performances vary for different catchments and more so with increasing terrain complexity means that there is no single model that can handle all sites with their different attributes. Negative correlation with the field-based scores means that results of the models for those catchments may be questionable. Accordingly, the USPED model may not be appropriate for the Maidelle catchment, which is relatively characterized by less curvature and gully erosion. The poor correlation could also be due to poor quality of DEM for relatively flat sites. The STCI and USLE2D models may not be appropriate for complex sites such as Laelaywukro.

Table 6.11: Correlation between field-based catchment characterization scores and results of models for each subunit of the four catchments in Tigray, N. Ethiopia.

Catchment	STCIsdr	USLE2Dsdr	USPED
Adikenafiz (n^1 = 12)	0.49	0.58*	0.60*
Gerebmihiz (n =14)	0.68*	0.63*	0.67*
Laelaywukro (n =11)	-0.41	-0.49	0.17
Maidelle (n = 4)	0.06	0.16	-0.84

*[1] Number of subunits each catchment is divided into; * significant at 0.05 level. Soil loss values for STCI and USLE2D were adjusted for SDR of each subunit based on equation 6.15.*

Good agreement between model results and field erosion sensitivity scores for the areas of high risk in the subunits of the catchments could help to identify landscape positions where management improvements should be prioritized. To evaluate this capability, the model results and field-scores of each subunit were plotted against each other (Figure 6.14). It can generally be seen that there is a positive correlation between model results and subunit scores for the higher soil loss categories. This may facilitate identification of areas more prone to erosion and therefore in relatively urgent need of management intervention.



(a) (b)

Figure 6.14: Relation between erosion sensitivity subunit scores and corresponding (a) STCI and (b) USPED model results for Gerebmihiz catchment in Tigray, N. Ethiopia. Similar agreements are observed for the other catchments

6.9 Discussion

6.9.1 Modelling soil loss rate: potentials and challenges

Soil erosion, being one of the most serious causes of land degradation, is putting tremendous pressure on productivity and environmental stability. Serious impacts raise the demand for conservation and management measures to reduce the magnitude of soil loss and the extent of its associated impacts. Soil erosion models are considered suitable means to monitor the process of soil erosion and quantify its magnitude (e.g., Lane et al., 1997; Sharma, 1998). Recent advances in DEM construction and associated algorithms to derive hydrological parameters and GIS allow to acquire and manage a great deal of data for catchment-scale applications (Moore et al., 1991; De Roo, 1998). This study demonstrates that models that do not require extensive and complicated data can be applied and provide a reasonable guide for further action. The more accurate and well calibrated the data that are used, the better the results and the better their benefits could be. The accuracy and calibration effort needed are mostly a reflection of the purpose for which the models are applied (Svorin, 2003; Jetten et al., 2003).

The models applied in this study are "terrain-based" whose LS factors have been improved to consider complex terrain configurations. One of the requirements in the application of such models is the calibration of the coefficients related to slope length and steepness, despite the fact that typical values of m and n are assumed to be between 0.4 – 0.6 and 1.0 – 1.4, respectively (Moore and Burch, 1986; Foster, 1990).

Exponents *m* and *n* in the *LS* factor equation are usually assigned based on slope gradient, type of flow, nature of surface cover and soil characteristics (e.g., Mitasova et al., 2001). Table 6.12 shows that using different possible values of *m* results in different *LS* factors (terrain potential for erosion), which could create huge differences in the estimated soil loss rates. This requires the need to calibrate the *LS* coefficients for local conditions. If no adequate calibration of the exponents is applied, the estimates should be considered as relative values.

Table 6.12: Possible *LS*-factor values for different exponents of m for some catchments in Tigray, N. Ethiopia.

	STCI			**USPED**		
	m = 4	m = 5	m = 6	m = 1.4	m = 1.5	m = 1.6
Adikenafiz	10.8	16.4	26.2	8.4	17.2	29.2
Gerebmihiz	6.7	9.9	15.3	3.6	9.0	17.7
Laelaywukro	15.5	22.3	34.0	6.3	13.5	25.0
Maidelle	4.2	6.4	10.2	4.8	9.8	16.7

S factor exponent (n) used for all above cases was 1.3. Calculation is based on multiple flow based routing algorithm.

Direct application of the (R)USLE-based KCP factors, which are mostly derived for simple plane fields and detachment-limited erosion to other locations and models without modification to obtain reasonable quantitative predictions for complex terrain conditions, may not be appropriate (Foster, 1990; Mitasova et al., 2001). The KCP factor values used in this study are based on KCP factors adapted for USLE-based erosion estimation for Ethiopia, which could affect their application to other models than the USLE. This could be the case especially for the USPED as Mitasova et al. (2001) suggested caution in interpreting results if direct use is made of the USLE-based KCP factors. The erosion values predicted by the USPED in this study are, however, in good agreement with sediment yield estimates.

Application of the models on a catchment scale requires distributed data. The accuracy of such data is determined by several factors, the most important of which are “position” of the cell and the “identity” assigned to each cell. In order to get reasonably accurate soil loss values, it is vital that all maps be geometrically registered to each other. A shift in one of the layers could lead to assigning wrong value to a particular cell and therefore arriving at a different soil loss/gain rate for that cell.

One of the key factors that dictates erosion/deposition processes is LUC. It is an integral part of all soil erosion models and its accurate delineation is crucial to handle the spatial patterns of erosion/deposition processes properly. Despite the fact that different satellite systems are available to detect and record spectral reflectance of features, extracting accurate information properties is difficult in environments like northern Ethiopia where the heterogeneity and complexity of parcels is high. This required intensive field survey to collect training areas so that the classification can be improved. Still, however, the most difficult and uncertain component of erosion models mainly when applied at catchment scale will remain to be extracting accurate LUC for each cell. The fact that the LUC maps have an accuracy of about 80% for instance means that some pixels could have been assigned a different LUC identity, which could then give a different soil loss value.

The scale at which the data are acquired and the cell size in which soil loss rates are calculated could also affect soil loss values (e.g., Zhang and Montgomery, 1994; Wilson and Gallant, 2000; Svorin, 2003). In most instances, coarse cell size could smoothen landforms in complex landscapes and result in artificial process results (e.g., Dikau, 1989), while very fine cell size may not have much added value compared to the costs incurred to acquire the necessary data (Quinn et al., 1991). Changing cell size to conform to other data sources could also alter real values and affect ultimate soil loss estimations. The methods involved in acquiring input parameters for erosion models could also affect the results of models (Svorin, 2003). Such problems could be more severe when extrapolation of point data to catchment scale is involved. Application of the models at catchment scale to derive accurate soil loss values for each cell may require very detailed data, which in many instances may not be collectable.

The type of flow routing algorithm employed also affects the rate and quantity of soil loss (Desmet and Govers, 1996b; Wilson and Gallant, 2000). For instance, application of single and multiple flow algorithms for the STCI model resulted in soil loss rates of 60 and 83 t ha^{-1} y^{-1} for Adikenafiz and 54 and 75 t ha^{-1} y^{-1} for Gerebmihiz catchments, respectively (with m = 0.5 and n = 1.3). Such rise of about 35% in soil loss between single and multiple flow algorithms could be significant. The differences are relatively lower for catchments with limited concentrated flow and low gully erosion.

The model results for the four catchments in this study were evaluated based on ^{137}Cs, soil profile and field-based data. Differences in the scale of observation of processes (such as the point data acquired for ^{137}Cs or soil profile versus the cell size of erosion modes) could have an impact on the comparison. The length of time over which processes took place could also influence the consistency of the final results. For instance, ^{137}Cs measures cumulative processes for over 50 years while the factors used in the models may not have accurate representation of this temporal scale. The soil profile data are results of long-time processes with events of different intensities taking place at different times and comparing such data with model results may create problem. The field survey data would be more biased by recent processes while model results consider relatively longer time spans. Application of models at catchment scale and interpretation of results therefore require careful analysis of processes at relevant temporal and spatial scales before conclusions are made and recommendations given.

The soil losses predicted given all the above uncertainties could have limited accuracy to quantify the rate of soil loss. In this study, the USPED model showed good agreement with sediment yield data, which encourages its application to the study region.

6.9.2 Spatial patterns of erosion/deposition and sediment source areas

Since the main target of land managers is to reduce the amount of on-site soil loss and its associated off-site effects, identification of critical areas that require intervention is crucial (e.g., Phillips, 1989; Jetten et al., 2003). To evaluate their usefulness for the implementation of management practices, the potential sediment source areas predicted by the different models were evaluated based on independent data of different types and sources. The quantitative and semi-quantitative approaches employed to evaluate the results of the different models show that the USPED model could generally be considered adequate to identify hot-spot areas of high runoff and erosion potential. The USPED model not only reflects erosion/deposition patterns better than the other two models, it also appropriately simulates potential locations and patterns of gullies and their relative contribution to sediment yield. The STCI could also be considered an option, since it has the capacity to identify critical areas of erosion and to some extent simulates the contribution of gullies and stream channels. It does not require detailed DEM like the USPED, which could make it attractive for data scarce regions. The USLE2D generally underpredicts soil loss, and its capacity to simulate possible areas of rill/gully erosion is limited compared to the other two models considering the four sites studied.

Generally, the results of the models show that the potential sediment source areas are located within the proximity of gullies and at high slope positions with poor surface cover. The higher and slopy areas in most cases are characterized by convex shape with accelerated flow, which can facilitate soil loss and ultimate delivery to downslope positions. On the other hand, model results generally predict low soil loss rates at low elevation and low slope gradients, with slightly higher erosion on cultivated fields and gullies.

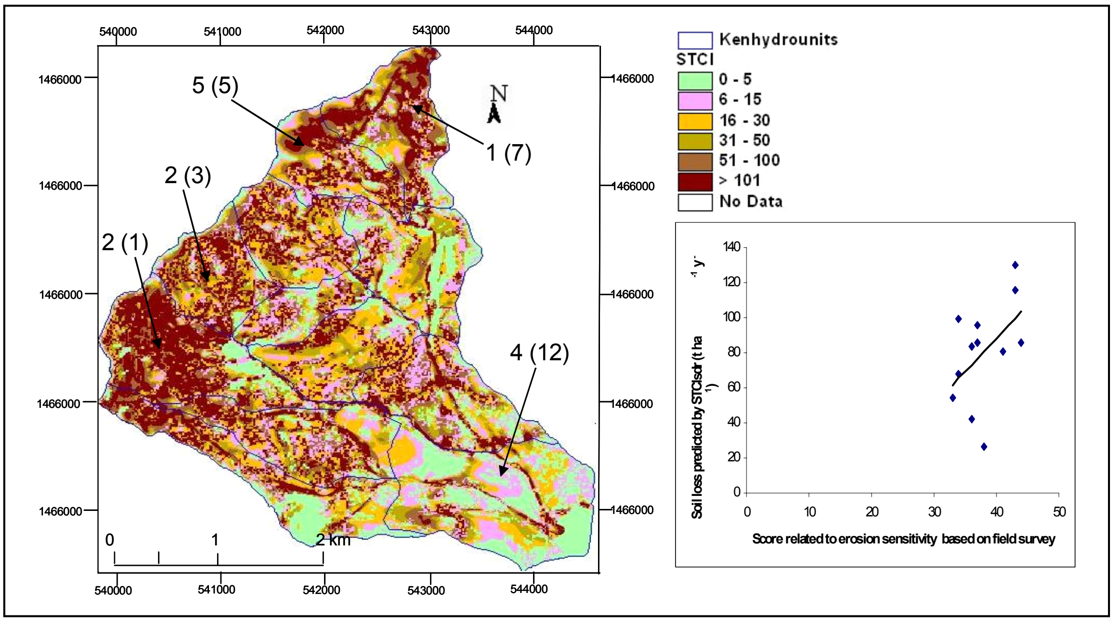
It is not necessarily true that all steep slope areas will contribute higher sediment compared to the gentle slope areas. Intensive land use with high soil disturbance is generally located on gentle slopes, while less intensive land use tends to occur on steeper slopes, in which case the separate effects of both topography and land use on catchment response become less evident (Rustomji and Prosser, 2001). For instance, the field-based catchment characterization shows that some of the upslope positions with steep slopes have less erodible cliffs (Figure 6.15a), which can be characterized as having high runoff but low soil material to be detached and transported. Some of the steep slope areas also have resistant lithology and good surface cover due to inaccessibility for grazing resulting in lower soil losses. On the other hand, the lower positions of catchments and piedmont sides are mainly characterized by rill/gully erosion with high delivery potential (Figure 6.15b). The low slope positions are intensively cultivated and overgrazed, which can lead to soil disturbance and accelerated erosion. Only the USPED model showed higher erosion rates at lower slope positions mainly associated with gullies and topographic hollows. The SERPU evaluation also showed such processes at lower slope positions.

By integrating the results of the model- and field-based approaches, five different landscape positions with high erosion rates and high sediment delivery potential were selected from each of the four catchments. In order to identify subunits where both field-based and model-based evidence show high soil loss risk and sediment delivery potential, results of each subunit (scores and model results) were compared. To be able to compare the field survey based scores with soil loss predictions by models of each subunit, the results were ranked in ascending order. This enables evaluating the potential of models for identifying areas of different erosion risk. The areas where the field-based scores and model-based results predicted high soil loss and sediment delivery potential (when field-based scores and high soil erosion rates coincided) may be considered as erosion sensitive requiring urgent intervention. Figure 6.16 shows the relations between the ranks of scores and results for the STCI and USPED models for two example catchments.

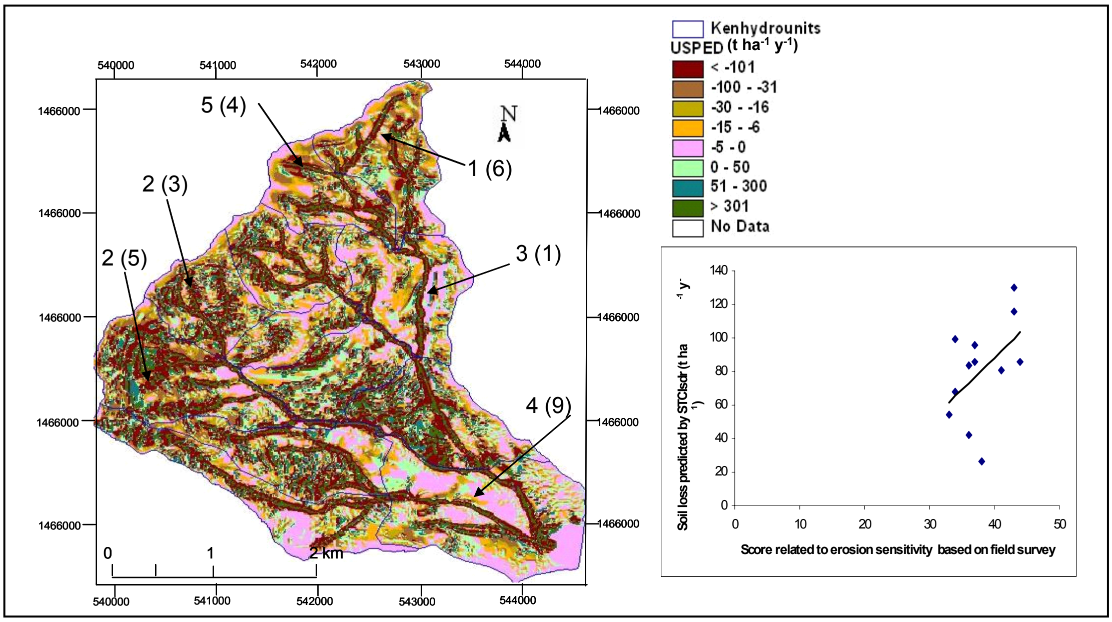
Figure 6.15: Different erosion intensity due to differences in the nature and status of erosion factors (a) Sandstone-dominated steep slope with low erodibility potential (b) gentle slope area characterized by gully erosion with intensive cultivation up to the very edge of the gully (Tigray, N. Ethiopia)

Generally, there is an agreement between the field-based scores and model-predicted soil loss rates in the relatively sensitive areas. For instance, comparing the ranks of subunits based on field-based scores and the corresponding erosion model results, shows the possibility to identify most of the areas that require priority in conservation planning using the model results. Subunits assigned with ranks from 1-5 (1 representing highest soil loss and decreases further) based on field observation coincide well with corresponding areas scored from 1-5 based on model results (Figure 6.16). Four out of the 5 landscape positions (subunits) with high erosion risk based on field survey also were identified for the Adikenafiz and Gerebmihiz catchments (Figure 6.16 b and d) based on the USPED model (rank 1-5). For some of the sites, differences between the scores and model results were observed mainly for subunits where slopes are not very steep but which are highly degraded due to intensive cultivation or overgrazing. A good example is the Gerebmihiz catchment (Figure 6.16 c and d) where a subunit identified to be very susceptible to erosion and sediment delivery based on field survey (rank 1) is categorized to have a $6^{th}/7^{th}$ rank based on model results.

The good correspondence between the field-based scores mainly at subunits with high soil erosion risk as well as the better correlation between the SERPUs and model results at high soil loss categories suggest that the models applied in this study could be used to identify hot-spot areas of erosion for planning of relevant management intervention. However, adequate field verification of model results should be a crucial step before results are used for intervention.

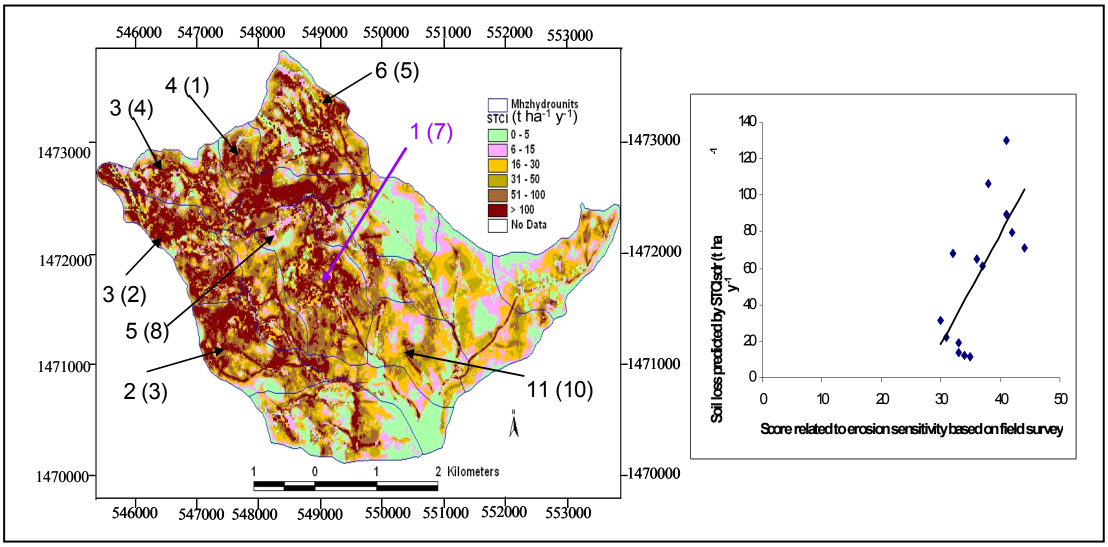


(a)



(b)

Figure 6.16: Spatial distribution of major sediment source and potential delivery potential sites based on STCI and USPED models for two example catchments (a & b, Adikenafiz) and (b & c, Gerebmihiz) in Tigray, N. Ethiopia. Numbers show rank assigned to each subunit considering field-based erosion assessment scores and soil loss of models. Ranks related model results are shown in brackets. Agreement at ranks of possibly 1-5 could show that the models are capable of identifying sensitive areas of erosion and can therefore guide prioritization of conservation measures. The graphs (right side of maps) show correlation between field-based erosion sensitivity scores and model-based soil loss rates of each subunit



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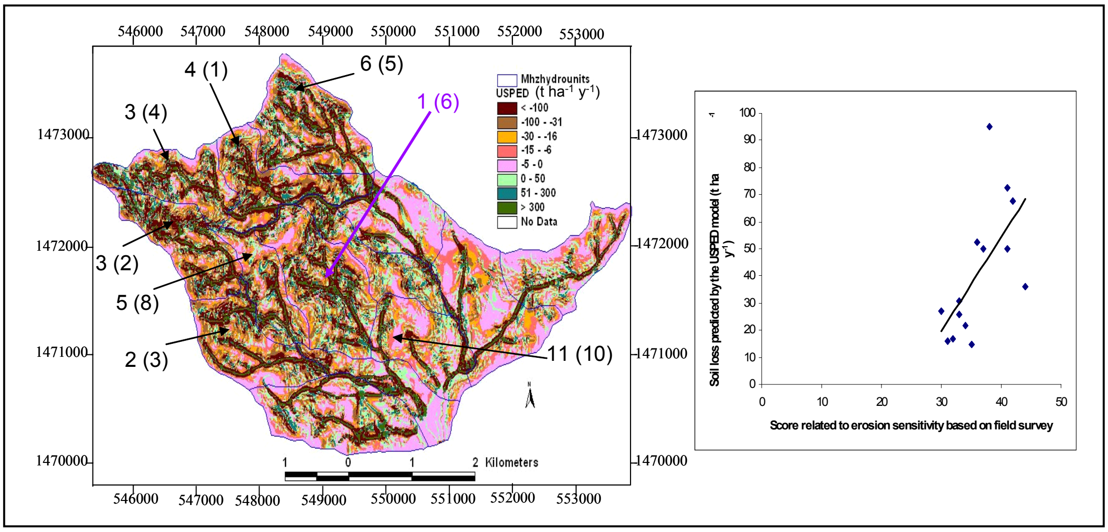


(d)

Figure 6.16: continued

6.10 Conclusion

The soil loss estimates predicted by the different models generally range between 15 to 80 t ha^{-1} y^{-1}. The wide soil loss range is due to differences in the attributes of the catchments, the way models handle terrain complexity and whether models consider deposition or not.

The model results suggest that application of a single type of model for different areas with heterogeneous attributes may not yield accurate results for all sites. It is also observed that adequate calibration of models is needed to derive reasonably accurate prediction of soil loss rates. Proper validation of models with adequate field data is also necessary to identify sites that are particularly important in terms of on-site erosion and sediment delivery potential. Putting all types of evidences together, the USPED model gives reasonably good estimates of soil redistribution in the studied catchments. The STCI could be a good option if only areas experiencing erosion are to be identified and SDR values can be calculated.

In general, the results of the different models show that the rate of soil erosion in most of the studied catchments is above the rate that can be tolerated. Based on the model results, a minimum of 40% (Adikenafiz and Gerebmihiz), 25% (Maidelle) and 30% (Laelaywukro) are eroding at a rate higher than the maximum tolerable soil loss rate of 18 t ha^{-1} y^{-1}. Such accelerated rates of erosion are responsible for the high rate of reservoir siltation in the region. Larger proportion of the sediments are derived from the upper parts of catchments and gullies. If the areas experiencing more than 30 t ha^{-1} y^{-1} of soil loss are considered to be in need of conservation, 35% and 45% of the Adikenafiz and Gerebmihiz catchments will require conservation practices, respectively.

Although most models predicted higher rate of soil loss on the slopy areas of the catchments, field observation and results of the USPED model show that the gently sloping areas of the catchments also have a high soil loss rate. Due to gully erosion and gully bank collapse of most of the floodplains, their sediment contribution per unit area could be higher than their role as sediment sinks. The contribution of stream/gully channels and banks to reservoir siltation requires due attention because the stream channel contribution may have greater impacts per contributed unit volume than other sources, as sediment can be delivered directly to reservoirs (Coleman and Scatena, 1986). Since most of the high soil loss rates are associated with gullies, conservation practices in such areas could reduce the off-site sediment delivery potential and associated siltation of reservoirs. The field observations in this study also suggest that gullies mostly occur in common grazing areas rather than in cultivated fields, which could be due to differences in management.

The results of this study demonstrate that models that are not complicated and data demanding can be applied to determine the spatial distribution of sites that require further analysis and management intervention. In general, the models enable identifying which landscape positions are more vulnerable to erosion and have a high sediment yield potential. This could enable providing simplified information to decision makers and planners with respect to where intervention is necessary to reduce soil loss from catchments and its delivery to reservoirs.

7 GIS-BASED SEDIMENT YIELD SIMULATION OF LUC-REDESIGN SCENARIOS

7.1 Introduction

In Ethiopia, reservoir siltation is one of the main threats of the water harvesting schemes and hydro-electric power dams (e.g., Ayalew, 2002). Soil erosion, aggravated due to intensive rainfall, fragile soils and absence of protective surface cover, is the major cause of rapid siltation. Population pressure and deforestation as well as cultivation of steep slopes, which accelerate erosion and siltation, are also becoming common phenomena in the country. Mechanisms for tackling erosion and degradation enhancing processes need, therefore, to be devised in order to protect siltation of water bodies, reduce nutrient losses and improve the food security of people.

Accelerated runoff and soil loss from catchments are responsible for rapid downstream siltation. Runoff and soil loss are both inversely related to ground cover (Costin, 1980). A densely vegetated soil surface has high surface roughness values in comparison to heavily grazed pasture or unprotected agricultural fields (Vought et al., 1995) and reduces the impact of raindrops and the ability of running water to detach and transport sediments (Laflen et al., 1985; Renard et al., 1997). Afforestation of upslopes and enhancement and maintenance of buffer riparian strips could, therefore, offer tremendous benefits with respect to reducing on-site soil loss and off-site siltation of water bodies (Erskine and Saynor, 1995; Millward and Mersey, 1999). Thus, appropriate land use and land management practices that maintain high ground cover are useful means to reduce soil loss and sediment delivery potential (Erskine and Saynor, 1995).

The effectiveness of land management towards preserving negative impacts of soil erosion in a complex landscape can be significantly improved by detailed predictions of erosion and deposition patterns for proposed land-use alternatives (Mitas and Mitasova, 1998b). Through simulating the impact of land use and land cover (LUC) changes on the spatial distribution of erosion/deposition, optimization of measures aimed at creating stable landscapes would be possible (Mitasova et al., 2000; Verstraeten et al., 2002b; Hessel et al., 2003; Stolte and Bouma, 2005). There is also a strong belief that through landscape or ecological restructuring it will be possible to apply targeted conservation measures and land-use practices, which can protect the environment and improve productivity (Vlek, 2001). A major step in the conservation planning process is, therefore, to evaluate and judge each component of a basin in terms of its capacity to support a given land use on a sustainable basis, by properly assessing the trade-offs related to ecological services on the one hand and the production/harvesting of ecological goods on the other (Vlek, personal com.). An appropriate approach could then be that erosion prone areas are set-aside to regenerate, and yield loss can be compensated through intensification of production on more resilient land elsewhere (Vlek, personal com.).

Soil erosion and sediment delivery processes vary across landscapes due to differences in the attributes of sites and the kinds of processes operating at different locations. As a result, all locations do not experience similar levels and patterns of soil loss and contribute equal sediment to downstream sites. A targeted response should be employed where resources are directed to areas of high risk rather than spreading them equally across the landscape (Adinaryyana et al., 1998; Boardman, 1998). In addition, limited financial resources and land-use activity restrictions forbid the application of conservation measures to all areas experiencing erosion. Consequently, it is necessary to identify hot-spot areas within catchments that are at high risk for which to prescribe site-specific management options. Distributed soil erosion/deposition models can be a useful means to predict erosion as well as to identify landscape positions experiencing high rates of soil loss compared to others. Model-based spatial scenarios can also be used to simulate ways of preventing soil erosion and its downstream delivery by designing alternative land use and conservation options targeted at specific locations (Hessel et al., 2003).

In this study, a distributed model was used in a GIS environment to identify areas of high erosion risk and simulate the effect of different LUC-redesign and conservation measures on annual erosion and its potential delivery. The simulation mainly focused on reorganizing LUC-types and conservation practices across the different landscapes based on predefined criteria such as gullies, slope, and intensity of erosion. The scenarios were run for two catchments in northern Ethiopia using the Unit Stream Power-based Erosion/Deposition (USPED) model integrated in a GIS. Nine different simulations were performed and the net soil loss/sediment yield rates were compared with those estimated based on the current/baseline condition.

7.2 Study area

For this study, two catchments with an area of 1400 to 1900 ha were selected in the Tigray region, northern Ethiopia (Figure 7.1). The landscape of the two catchments is generally rugged terrain dissected by gullies. Land use is dominantly arable with different proportions of pasture and scattered bush/shrub covers. The major lithology is shale intercalated with limestone with mountain tops covered by sandstone. Soils are dominantly leptosols on the upslope positions, cambisols on the middle slopes and vertisols at locations around and behind reservoirs. Soils are highly erodible and terrain erosivity potential is high. Surface cover is also poor, which facilitates erosion processes. The two catchments are thus among the most eroded with high sediment deposition in reservoirs.

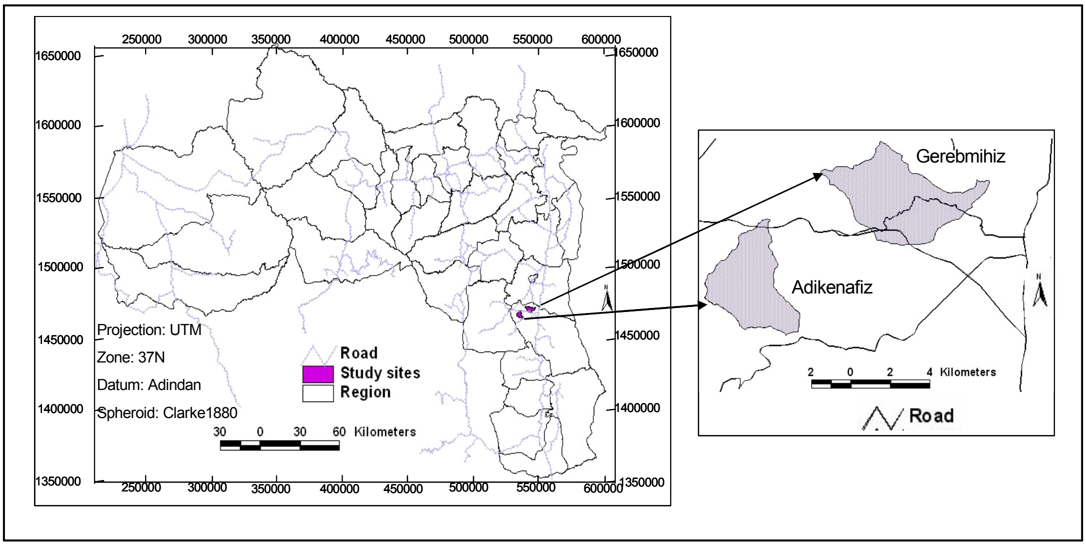


Figure 7.1: Location of Adikenafiz and Gerebmihiz catchments in Tigray, N. Ethiopia

7.3 Methodology

7.3.1 Model description and input

The USPED model (Mitasova et al., 1997, 1999, 2001) was used to predict the spatial patterns of erosion/deposition and simulate the effects of LUC-redesign and conservation practices on soil loss and reservoir sediment deposition in the two study catchments. This model was selected because the annual net soil loss from catchments predicted by the model very well agrees with annual sediment deposition in reservoirs. For four selected catchments, the annual net soil loss predicted by the USPED model has shown a very strong correlation with annual sediment deposition in reservoirs (Pearson's r > 0.97, sig. 0.001). The square root of mean square error, which compares the observed (reservoir-based) and predicted (USPED-based) annual soil loss/sediment yield estimates, also shows that the overall error of the USPED model was less than 5 t ha^{-1} y^{-1}. Thus, net soil losses predicted using the USPED model for the 2 catchments can be associated with annual sediment yield in the corresponding reservoirs with high confidence limit. The capacity of the model to simulate the spatial patterns of gullies and predict their soil loss also makes it suitable to the study region as gullies are major sources and agents of reservoir siltation. In addition, the model can be applied with minimum data compared to other process based models.

Since catchment erosion is the main cause of reservoir siltation, effective reduction of siltation can be achieved by tackling soil erosion upslope through conservation/management activities. It is also indicated that conservation of upslope areas is more effective to reduce downstream siltation than outlet-based approaches (Verstraeten et al., 2002b). The USPED model was, therefore, used to identify major sediment source areas and simulate the effects of reorganizing LUC to reducing soil loss and reservoir siltation.

To carryout the simulation, the catchments were first divided into grid-cells of equal size (10 m), and relevant terrain attributes were derived. Other erosion factors such as erodibility (K), cover and management (C) and support practice (P) were also derived for each grid cell. The erosivity (R) factor was calculated considering the average rainfall of 35 years, and this value was maintained during the simulation. Details of the procedures employed to derive the different erosion factors are outlined in Chapter 6.

7.3.2 Scenario description

Preventing the rapid siltation of reservoirs requires an understanding of the causes and processes responsible, so that cause-treatment-based corrective and preventive measures could be taken to ameliorate the problem. Because of the spatial variability of erosion severity and the difficulty in implementing conservation measures to all areas, identification of sites that require prior intervention will be necessary. In this study, landscape positions for simulating the different scenarios were identified considering gullies, slope, and rate of current soil loss with the aim of tackling the erosion problem at the source and during transport (Horswell and Quinn, 2003). After potential areas of intervention were prioritized, several LUC-redesign and conservation scenarios were applied, and the resulting sediment yield was compared with the existing/baseline condition. Ten scenarios (including the one that represents the baseline condition) were simulated (Table 7.1).

The first scenario calculates net soil loss/sediment yield based on the existing conditions of the erosion factors. The second scenario was based on conservation of gullies and their buffer zones using grass strips and terraces. A set of set-aside scenarios, whereby areas above a given slope or soil loss threshold were taken out of their current use (arable farming or livestock grazing) and transferred to a less-erodible types of land use (e.g., dense grass or forest cover), were tested in scenarios 3 and 4. Brief descriptions of each scenario are presented below.

Scenario 1: Existing soil loss from catchments/deposition in reservoirs

The status quo annual soil loss/sediment yield rate and its spatial pattern were determined using erosion factors that represent the current conditions. The result was then used as a benchmark against which the result of each simulation was compared.

Scenario 2: Management/conservation measures targeting gullies

Studies have shown that areas with prominent gullies have high catchment connectivity and sediment delivery potential and serve as efficient pathways for sediment transport to rivers or reservoirs (e.g., Steegen et al., 2000; Poesen at al., 2003). Field observations and interviews of local farmers and experts in the study area highlighted that gullied catchments experience a higher siltation risk than those with fewer gullies. One of the scenarios was, therefore, targeted at conserving gullies with the aim of reducing their sediment contribution as well as retarding their sediment delivery efficiency.

Check dams along gullies and grass buffers are often considered as important and cost-effective measures for reducing the sediment delivery to rivers (e.g., Haan et al., 1994; Borin et al., 2005). Buffer vegetation, especially grass, acts as a filter by increasing surface roughness. It augments infiltration and decreases flow volumes and speed, ultimately reducing the transport capacity of runoff and encouraging sediment deposition in the buffer strip (Rose et al., 2002). Scenario 2 targeted conservation measures at gullies and their 25-m wide environs to stabilize them, protect them from collapsing, trap sediment along their course, and to trap sediment along the edges of gullies before it entered the course. In the model, the gullies and their 25 m wide buffers were therefore terraced (P factor 0.6)[9] and seeded with dense grass (C factor 0.01)[10], forming a stable grassed waterway along their route to the reservoirs (Verstraeten et al., 2002b). The 25 m buffer was intended to include areas along concentrated flow that experience high soil loss based on the USPED model.

Table 7.1: Summary of LUC-redesign and conservation based scenarios for the Adikenafiz and Gerebmihiz catchments in Tigray, N.Ethiopia.

Scenario	Description
1	Current condition
2	Current condition with 25-m gully buffer terraced and grassed
3a	Current condition with areas over 25% slope set-aside and enclosed
3b	Current condition with areas over 15% slope set-aside and enclosed
3c	Current condition with areas over 25% slope enclosed and gully buffer terraced and grassed
3d	Current condition with areas over 15% slope enclosed and gully buffer terraced and grassed
4a	Current condition with areas experiencing soil loss of more than 50 t ha^{-1} y^{-1} enclosed
4b	Current condition with areas experiencing soil loss of more than 25 t ha^{-1} y^{-1} enclosed
4c	Current condition with areas experiencing soil loss of more than 50 t ha^{-1} y^{-1} enclosed and gullies terraced and grassed
4d	Current condition with areas experiencing soil loss of more than 25 t ha^{-1} y^{-1} enclosed and gullies terraced and grassed

Scenario 3: LUC-redesign targeting 'steep slope' areas

Slope influences flow rates of water and sediment by controlling the rate of energy expenditure or stream power available to derive the flow (Zevenbergen and Throne, 1987). Generally, as slope gradient increases, runoff and soil loss also increases (e.g., Moore et al., 1991). The management implication of the direct relation between slope

[9] P factor values for support practices were defined for Ethiopia by Hurni (1985). Important values include ploughing up and down = 1.0; ploughing on contour = 0.9; strip cultivation = 0.80; terraces = 0.6; protected areas = 0.50.

[10] C factor values for Ethiopia were defined by Hurni (1985) for different cover types. Important values include Ethiopian Teff = 0.25; cereals/pulses = 0.15, sorghum/maize = 0.10; bush/shrub = 0.02; dense grass = 0.01; dense forest = 0.001.

steepness and soil erosion is that conservation practices focused on steep slopes could reduce the rate of soil loss and its downstream delivery. There is also an understanding that filling or removing gullies alone would not be sustainable, as gullies can develop again unless upslope areas are covered with vegetation (Adinarayana, 1995). During the simulation, areas with slopes of more than 25 and 15% were, therefore, converted to enclosures (C factor = 0.01), areas protected from human and livestock intervention. The C factor value of 0.001 (dense cover) was not used, considering the fact that achieving a "dense forest" cover in the existing environmental condition of the study areas may not be possible, at least not in the short run. The possible reduction of soil loss/reservoir sediment deposition after the LUC-redesign was calculated to assess the influence of upslope surface protection in retarding sediment yield. In addition to this, simulation was run with terraced and grassed gullies (scenarios 3c and 3d) to assess the impact of integrated management on net soil loss/sediment yield reduction.

The threshold slope classes were defined after experimenting with higher slope gradients and noting the reduction in net soil loss/sediment yield. Sediment yield reduction when targeting areas of slopes steeper than 30% was not significant. When targeting gentle slope areas of less than 15%, the proportion of farm lands to be set-aside from cultivation was high, which might have significant effects on the livelihoods of the farmers. Sediment yield reductions after enclosing areas with slopes of higher than 25 and 15% were therefore simulated in this study.

Scenario 4: LUC-redesign targeting hot-spot areas of erosion

Benefits of conservation measures can be more rewarding and sustainable if interventions are made in areas where they are needed most. The scenarios at this stage were based on targeting hot-spot areas experiencing high soil loss. In Ethiopia, soil conservation measures are recommended whenever soil loss rates exceed 16 – 20 t ha^{-1} y^{-1} (WAPCOS, 1990). In this study, the threshold values for categorizing areas of soil loss (scenarios 4a and 4b in Table 7.1) were chosen such that a soil loss of more than 25 t ha^{-1} y^{-1} was not acceptable, and the existing cultivation should not proceed at such locations. This threshold was partially based on the maximum tolerable soil loss of 18 t ha^{-1} y^{-1} (Hurni et al., 1985) and soil formation rates of 6 t ha^{-1} y^{-1} (Hurni et al., 1983a,b) estimated for the country. In addition, the 50 t ha^{-1} y^{-1} threshold was used to evaluate how far sediment yield reduction can be achieved in relation to the proportion of land taken out of cultivation, if the threshold soil loss value is doubled. During the simulation, the areas experiencing a soil loss rate of higher than the two thresholds were covered with a dense cover (C factor = 0.01) and net soil loss/sediment yield calculated for each (scenarios 4a and 4b). In addition, simulations were performed by including conservation of gullies along with enclosing erosion-prone areas (scenarios 4c and 4d).

7.3.3 Scenario simulation

After the types of simulations were defined based on where to apply which type of management/conservation activity, the different scenarios were run in a GIS using the USPED model. First, soil loss/sediment yield was simulated based on status-quo conditions of terrain, rainfall, LUC, and support practices. Then, the successive scenarios were performed and the results compared with that of the first scenario. Percentage net soil loss/sediment yield reduction in relation to proportion of cultivable land to be set-aside and areas to be enclosed were then analyzed for each scenario.

7.4 Results

Table 7.2 shows the amount of net soil losses from catchments/depositions in reservoirs after each LUC-redesign and conservation scenario. It also shows the proportion of cultivable fields to be forgone and areas to be enclosed (afforested) for each scenario. Figure 7.2 shows the rate of soil loss/sediment yield simulated for each scenario. The distribution of LUC-types and spatial patterns of soil loss for example scenarios are shown in Figure 7.3. Brief descriptions of the results are given below. The average results for the two catchments are discussed together.

Scenario 1: Current net soil loss/reservoir deposition rates

Scenario 1 shows the net annual rate of soil loss/sediment deposition in reservoirs of the two catchments under status-quo. The net soil loss/sediment yield during this scenario was over 78000 t y^{-1} (Figure 7.2). According to this rate of sediment deposition and based on an average original dead storage capacity of 140,000 m^3 (Table 3.1), the reservoirs have lost more than 100% of their dead storage capacity. This means that the reservoirs have lost their anticipated capacity to store sediment for their design life in less than 25% their age. Considering an average live storage (normal pool level) of 685,000 m^3 and the above rate of deposition, it can be estimated that the reservoirs have lost more than 45% of their storage capacity in less than 25% of their service time. With the above rate of siltation, the reservoirs could loss their total live storage capacity in less than 50% of their projected service time.

Figures 7.3b and 7.3f show the spatial pattern of soil loss from the catchments for the existing condition. Generally, most of the sediment source areas are located on high slope areas of cultivated fields whereas lower slope positions show low amount of sediment loss despite their poor surface cover. However, the lowland flood plains, mainly gullies and valley sides, also contribute high sediment (Figure 7.3b, f).

Table 7.2: Soil loss/sediment yield, proportion of cultivable land to be set-aside and areas to be enclosed during each simulation for two catchments in Tigray, N. Ethiopia.

Scenario	**Adikenafiz**			**Gerebmihiz**		
	Soil loss ($t\ y^{-1}$)	**Cultivated land foregone[1]**	**Area to be enclosed[2]**	**Soil loss ($t\ y^{-1}$)**	**Cultivated land foregone[1]**	**Area to be enclosed[2]**
1	71465			83750		
2	38916	4	---	34758	3	---
3a	65514	10	25	69042	8	14
3b	57003	31	49	59006	15	32
3c	36202	15	19	30043	10	13
3d	34190	33	40	27589	23	31
4a	38498	20	29	38150	11	26
4b	38352	27	38	37730	24	35
4c	28599	24	27	22336	18	24
4d	28412	30	30	22156	29	35

[1] Indicates the proportion of cultivated land (%) to be set-aside and enclosed. [2] Indicates the proportion of land (%) to be forested (enclosed), without grassed gully buffers.

Scenario 2: Soil loss/sediment yield scenario after conservation of gullies

Scenario 2 (Table 7.2 and Figure 7.2) shows net soil loss/sediment yield after specific conservation measures were simulated targeting gullies and their 25 m buffers. Results of this scenario show that the rate of annual reservoir sediment deposition could be reduced by 53 % through conservation of gullies including exclusion of livestock from disturbance and avoidance of cultivation up to the very edge of gully banks. This reduction could be accomplished with < 5 % of agricultural land to be set-aside.

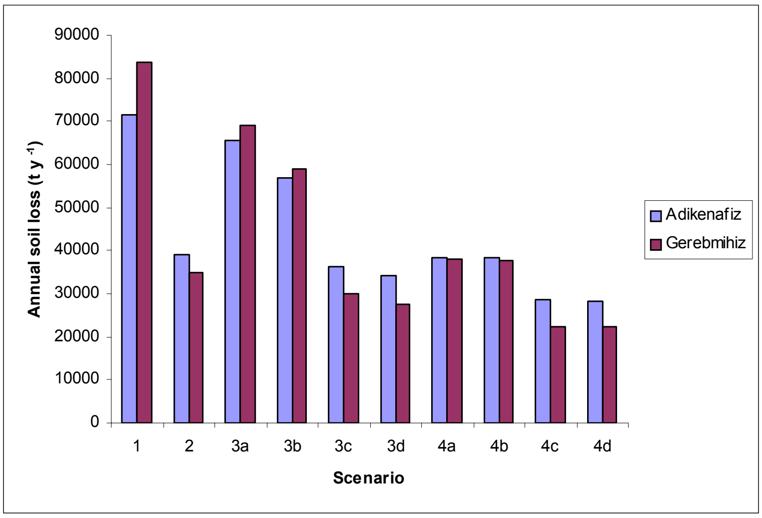


Figure 7.2: Annual soil loss/sediment yield rates simulated based on the different scenarios (Table 7.1) for Adikenafiz and Gerebmihiz catchments in Tigray, N. Ethiopia (1 = states quo; 2 = gullies; 3a = slope > 25%, 3b = slope > 15%; 3c = slope > 25% and gullies; 3d = slope > 15% and gullies; 4a = soil loss > 50 t ha^{-1} y^{-1}; 4b = soil loss > 25 t ha^{-1} y^{-1}; 4c= soil loss > 50 t ha^{-1} y^{-1} and gullies; 4d = soil loss > 25 t ha^{-1} y^{-1} and gullies)

Scenario 3: Soil loss/sediment yield scenario after conservation of slopes

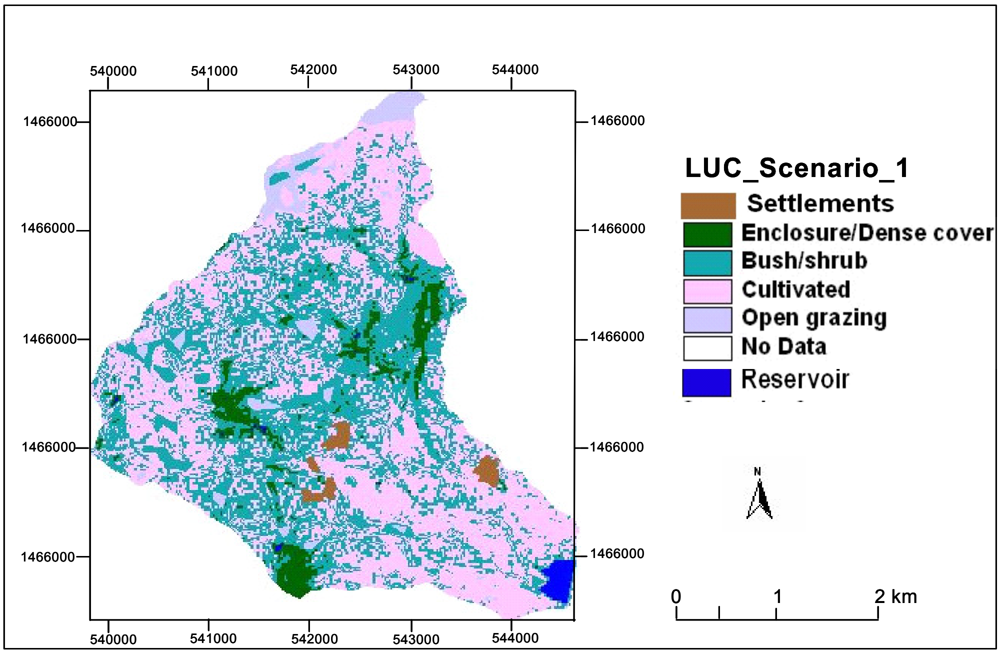
This scenario shows that when areas with slopes of more than 25% are enclosed, a sediment yield reduction of over 13% can be achieved (scenario 3a). When slopes of higher than 15% are enclosed, the reduction can be 25% (scenario 3b).

When conservation of gullies is combined with afforestation of areas with steeper slopes, the sediment yield reduction improves further (scenarios 3c and 3d). When slopes of over 25% are enclosed and gullies terraced and covered with dense grass, an overall sediment yield reduction of 57% was achieved (scenario 3c) and for afforestation of slopes over 15% and conservation of gullies, a sediment yield reduction of about 60% was simulated.

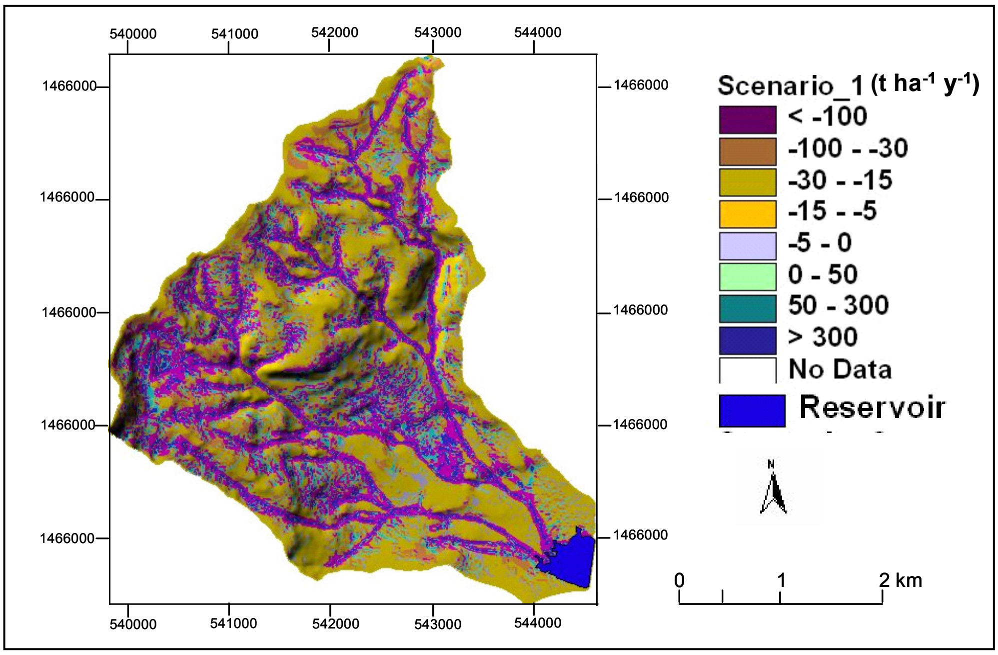
Scenario 4: Sediment yield scenario after conservation of hot-spot areas of erosion

When areas experiencing a soil loss rates of more than 50 t ha^{-1} y^{-1} were afforested, a sediment yield reduction of about 51% could be achieved (scenario 4a). Scenario 4b simulates the sediment yield reduction if areas targeted were those experiencing annual soil loss rates of higher than 25 t ha^{-1}. During this scenario, sediment yield could also be reduced by about 51%. The sediment yield reduction for the two cases was about equal because areas experiencing soil loss between 25-50 t ha^{-1} y^{-1} were small.

In addition to the above scenarios, gullies were also included in the management practice (scenarios 4c and 4d). The percentage sediment yield reduction when integrated management of both erosion-sensitive areas (experiencing soil loss rate of over 50 t ha^{-1} y^{-1}) and gullies was applied was about 67%. When conservation of areas experiencing soil loss rates of over 25 t ha^{-1} y^{-1} combined with conservation of gullies was simulated, the sediment yield reduction was also about 67%.

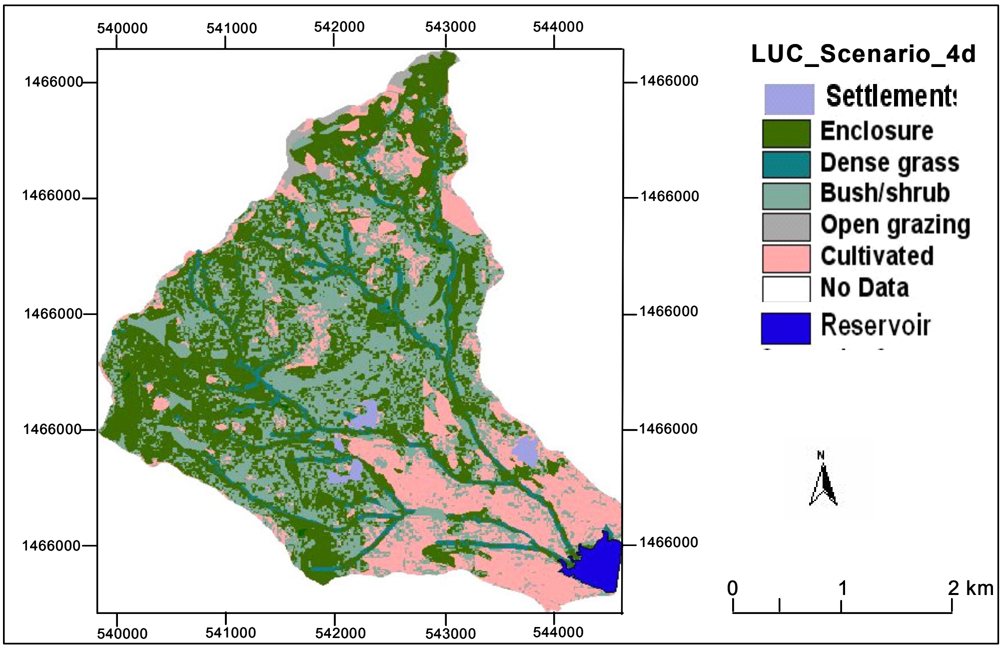


(a)



(b)

Figure 7.3: LUC- types and spatial patterns of soil loss rates for 2 catchments in Tigray, N. Ethiopia simulated based on scenarios 1 (status quo) and 4d (soil loss > 25 t ha^{-1} y^{-1} and gullies conserved) (a - d, Adikenafiz catchment and e - h, Gerebmihiz catchment). Note that the erosion/deposition maps are draped over DEMs



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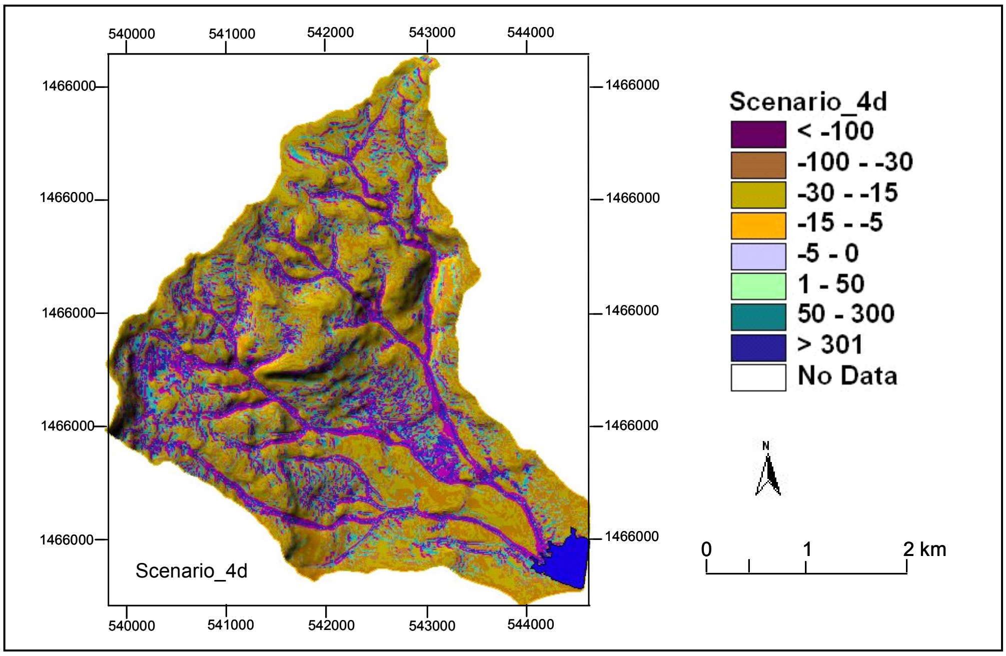

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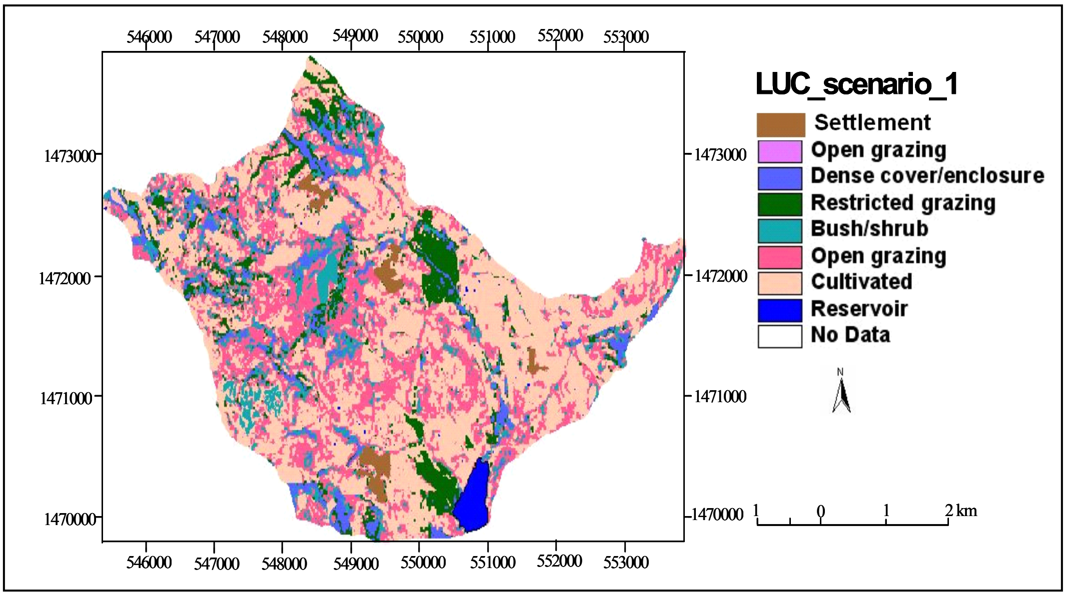

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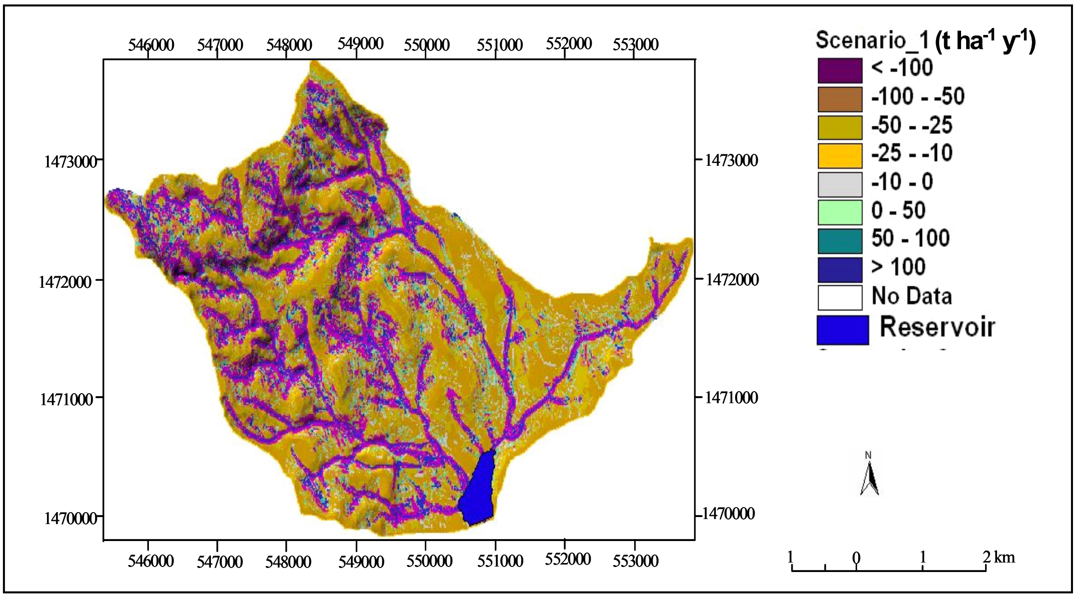

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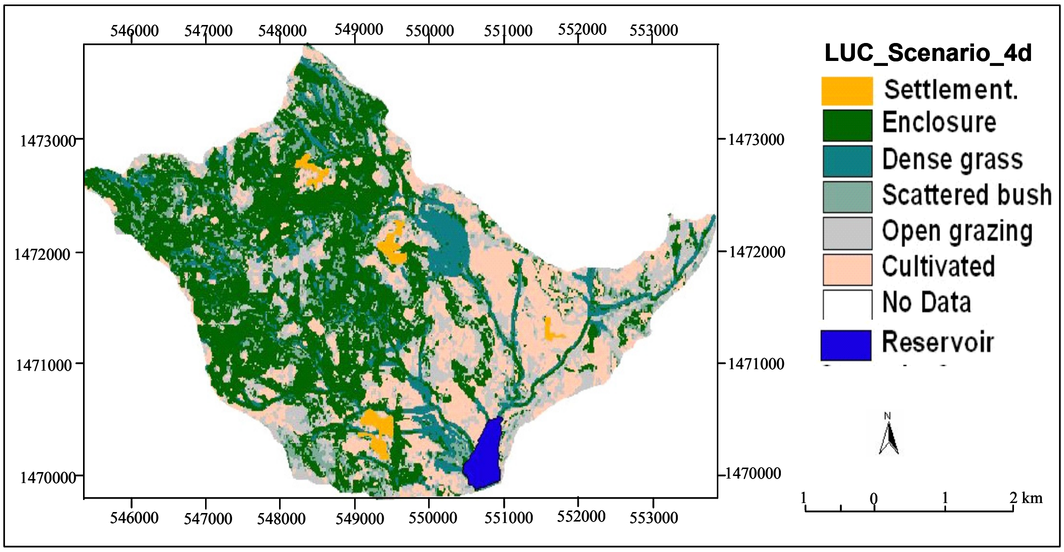

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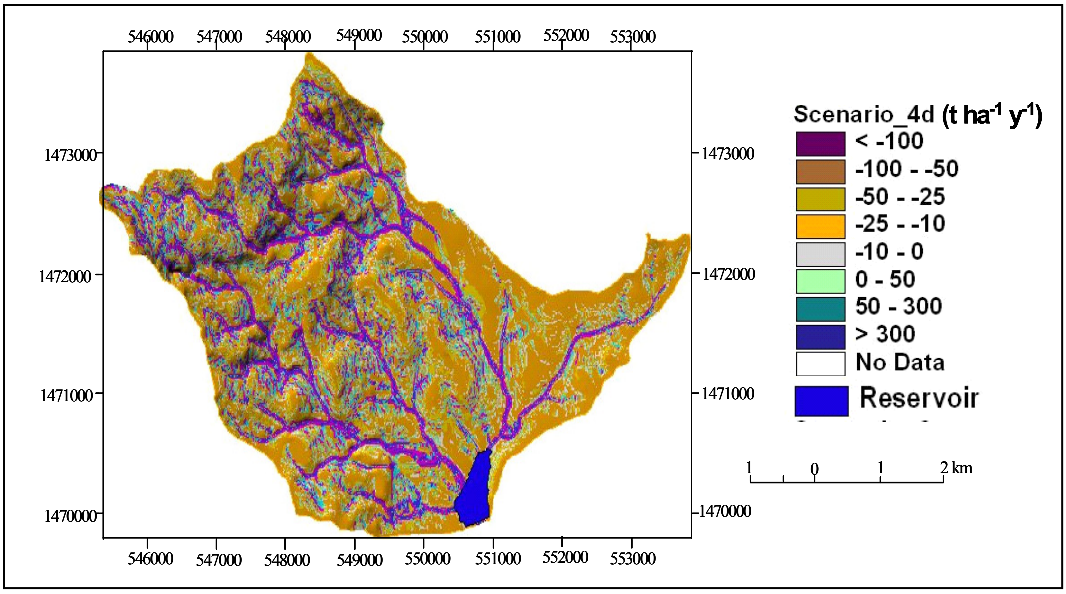


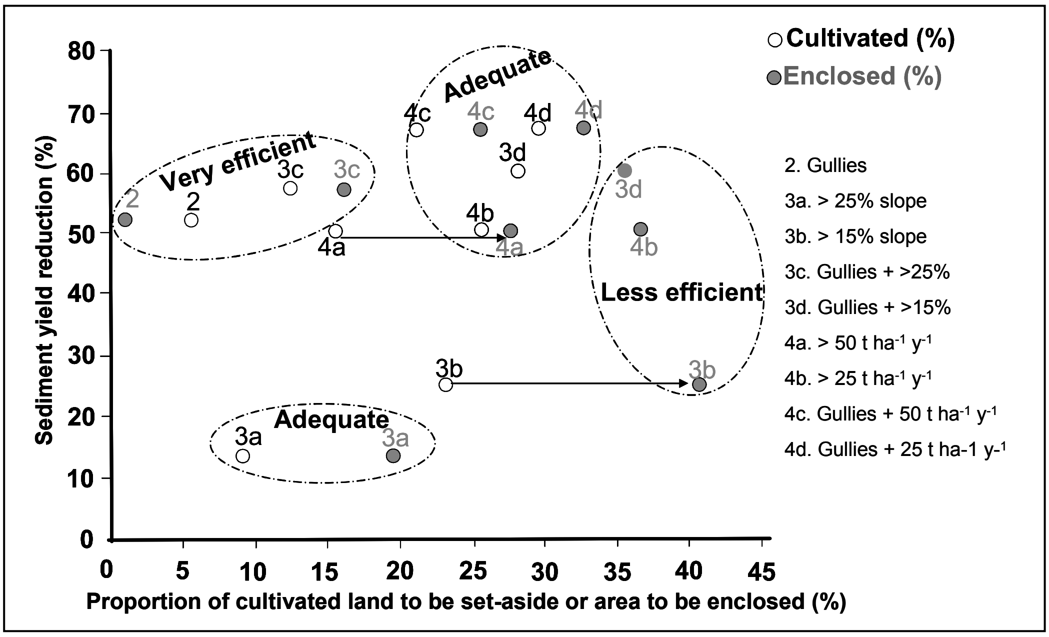
(h)

Figure 7.3: continued

7.5 Discussion

Figure 7.4 shows the percentage sediment yield reduction for percentage cultivated land to be set-aside and percentage area to be enclosed. The results show that sediment yield reduction is a function of the type of management practices applied and their location.

A study in eastern part of Ethiopia shows that gullies alone could contribute soil loss rate of about 25 t ha^{-1} y^{-1} (Shibru, 2003). Conserving gullies could therefore significantly reduce soil loss and downstream delivery. The simulation results in this study show that targeting gullies alone could reduce sediment yield by more than 50% while the proportion of cultivable land to be set-aside is low and the proportion of areas to be enclosed is small (Figure 7.4). The relatively high sediment yield reduction achieved by only targeting gullies and their buffers shows the importance of gully erosion on soil erosion and sediment delivery. High amount of sediment trapped on the terraced gullies in the study areas also demonstrate the benefit of managing gullies and their surroundings to reduce sediment delivery to reservoirs. Conservation of gullies reduces sediment yield better in the Gerebmihiz catchment than in the Adikenafiz catchment, which is mainly because the model predicted a higher level of gully erosion in the former than in the latter.



(a)

Figure 7.4: Proportion of sediment yield reduction in relation to percentage arable land to be set-aside and proportion of area to be enclosed for each scenario for two catchments in Tigray, N. Ethiopia

The simulations targeted to modify steep slope areas through increasing frictional resistance by dense cover show a less significant reduction in soil sediment yield. Scenario 3a, for instance, shows that by withdrawing less than 10% of the cultivable fields located at slopes of more than 25%, a sediment yield reduction of about 15% can be achieved (Figure 7.4). The sediment yield reduction increases to about 25%

when areas with slopes of more than 15% are excluded from cultivation (scenario 3b). However, this is at the expense of setting-aside a higher proportion of cultivable land (about 25%) and enclosing about 40% of the areas (Figure 7.4).

Scenarios 3c and 3d show simulations after conservation of both upslopes and gullies were applied. The integrated management practices show a high reduction of sediment yield (compare results of scenarios 3a and 3c versus 3b and 3d, Figure 7.3 and Figure 7.4). The two scenarios show a sediment yield reduction of about 55% and 60%, respectively. These could be achieved with about 15% and 25% of cultivated land to be set-aside for scenario 3c and scenario 3d, respectively. Scenario 3c will also require enclosing about 15% while scenario 3d will be achieved if about 25% of sites is to be enclosed.

When conservation measures targeting areas of high soil loss risk were applied, a further sediment yield reduction was achieved (scenarios 4a - 4d). By conserving areas with soil loss rates of higher than 50 t ha^{-1} y^{-1}, which account for about 30% of the total area of the catchments, an average sediment yield reduction of over 50% could be achieved. But, about 30% of the catchments with a high rate of soil loss would need to be afforested and protected from livestock interference. This is more than can be obtained when areas with slopes higher than 15% are enclosed (sediment yield reduction of about 25%). This was because, high soil loss risk areas were apparently not selected by the model when the given slope thresholds were used. This could happen when areas of steep slope and high soil erosion do not have a very strong correlation. This may also be due to the fact that steep slope areas, which are mostly characterized by rock outcrops and resistant lithology, may not necessarily be major sediment sources. The steep and relatively inaccessible areas are also characterized by bush/shrub cover and are less impacted by livestock overgrazing and soil crusting which reduces runoff and erosion.

The best achievement in terms of sediment yield reduction was when protecting hot-spot areas experiencing more than 25 t ha^{-1} y^{-1} – 50 t ha^{-1} y^{-1} and gullies were simulated. By protecting these areas, it could be possible to reduce sediment yield by over 65%. This can be achieved by excluding about 30% of the areas from cultivation and enclosing them with protective surface cover. This shows that application of conservation measures to protect erosion sensitive areas before and after dam construction could increase the productive life of the reservoirs by more than 50% compared to the current trend (a storage capacity loss of about 55% when no conservation versus about 17% when conserving hot-spot areas and gullies). This could be a big socio-economic and environmental benefit to the people and the region.

In general, high soil loss reduction per intervention is achieved for Gerebmihiz catchment than Adikenafiz catchment. However, this achievement requires relatively larger proportion of areas have to be enclosed with protective surface cover. On the other hand, higher proportion of soil loss reduction can be achieved for the Adikenafiz catchment per intervention, but requires relatively higher proportion of cultivated land to be set-aside. This shows that, while absence of protective surface cover is the crucial factor that resulted in high sediment yield in the case of the Gerebmihiz catchment, it is cultivation practice (mostly of slopy areas) that cause higher rate of reservoir siltation in the case of the Adikenafiz catchment. This indicates that management interventions should be site-specific and universal prescription of measures may not be effective for all sites.

The different scenarios show different soil loss/reservoir deposition reduction depending up on the areas of intervention. The choice of the better measure can be made by roughly comparing the benefits due to sediment yield reduction to the costs mainly due to exclusion of some arable lands from cultivation. If the proportion of cultivable land to be set-aside is compared with the proportion of sediment yield reduction (Figure 7.4), it can be seen that the model can be considered more efficient for scenarios 2 and 3c (which are associated with gullies) while it can be considered less efficient for scenarios 3d and 4b. Scenarios 3d and 4b are less efficient because relatively large proportion of cultivable land would otherwise need to be enclosed to arrive at similar proportion of sediment yield reduction. The rest could be just adequate because the proportion of soil loss reduction and areas to be set-aside or protected are about linear. The model performs better when gullies are included in the conservation activity which shows that the type of model used for the simulation purpose should be the one that can handle the major causes and erosion processes in the catchments. A model less sensitive to surface curvature and therefore topographic swales may not be very efficient for areas where gullies play significant role.

Figure 7.5 shows the possible reduction in reservoir storage capacity loss for each scenario. This figure also shows that scenarios involving gullies give higher improvement in maintaining the storage capacity of reservoirs compared to the others.

A preliminary assessment of the trade-off of each landscape position in terms of its productivity and conservation requirement can be conducted to evaluate if setting-aside a given fraction of land is worthwhile. For instance, if the areas to be set-aside have limited agricultural productivity, enclosing them may be an appropriate and efficient intervention despite the proportion of the areas to be set-aside. In most cases, areas where high soil loss is experienced are either not under current cultivation or are not properly managed and do not have a high potential productivity. Excluding such areas from cultivation may not have a significant effect on the livelihoods of farmers if the productivity of those areas is already low. Detailed socio-economic impact assessment would however be necessary.

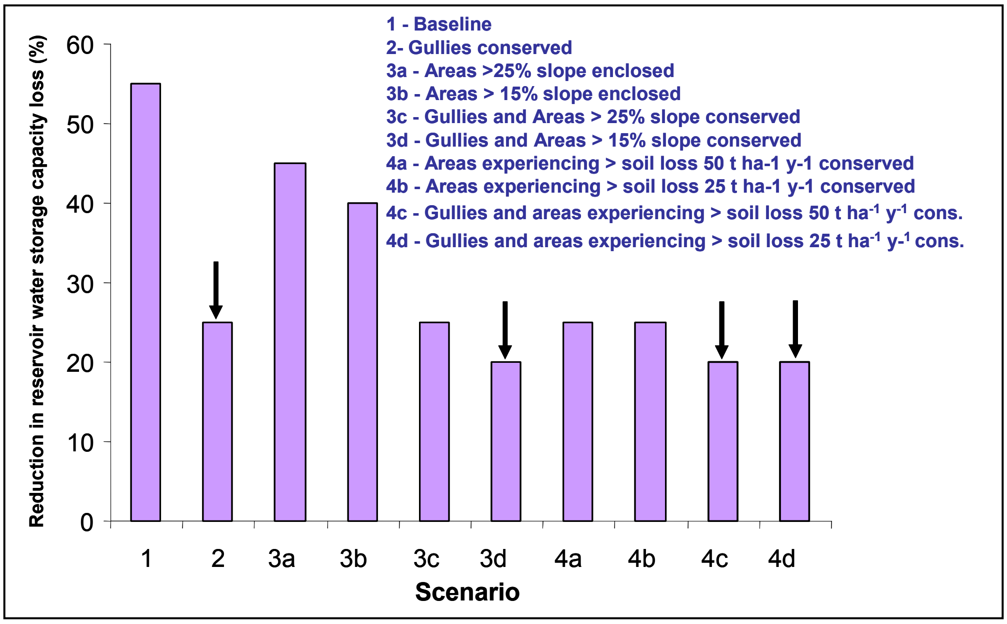


Figure 7.5 Reservoir storage capacity loss reductions in relation to the different scenarios for two catchments in Tigray, N. Ethiopia

The management and conservation strategies employed in this study require that some proportion of cultivable land or grazing fields need to be set-aside and enclosed. This will have an impact on the livelihood of the local farmers, and the measures may not be acceptable at least in the short term. However, in the long term, the enclosures will have an added value by not only reducing soil erosion and delivery but also by providing sources of feed for livestock, wood for construction or cooking, sequestering carbon and improving soil fertility, and by also improving the microclimate of the areas. Availability of livestock feed can reduce the collection of straw and other livestock remnants from the fields, which can improve soil fertility. Arrangements can also be made to entitle those farmers whose land is enclosed to benefits from the goods produced in the enclosures and any land productivity improvements associated with the newly introduced schemes.

In order to ensure active involvement of the farmers within the catchments and avoid potential conflicts between land users, arrangements can be made such that farmers whose land was taken out from cultivation could share benefit from the increased irrigable land downstream (due to reduced siltation). It may also be possible to increase the productivity of land downstream, so that the benefits forgone when some fields are taken out of cultivation can be compensated for. In cases where the proportion of cultivable fields taken out of cultivation is high and can not be compensated for through intensification of cultivation at other locations, government incentives may be necessary. This could help to support farmers in the short term until resource exploitation from the enclosures provides support. Mechanisms may also be designed to grow “trees” in the enclosures, which can provide income for the local farmers. It may also be necessary to assess if introducing agroforestry systems could contribute in reducing sediment yield. Redesigning some cereal crop lands to agroforestry can improve productivity and add value to the land to be set-aside. It also needs to be evaluated whether a reasonable soil loss reduction can be achieved when crops with good protective cover such as sorghum are grown on relatively steep slopes and those with low protective cover such as teff and cereals are cultivated on the lower slopes. Encouraging farmers to be engaged in off-farm activities and creating conducive environment for land use trading can also reduce the dependence of farmers on the less productive and fragile lands.

7.6 Conclusion

The simulation results demonstrate that an alternative land use can result in a reduction of sediment yield by about 15-65%. The maximum reduction was achieved when areas experiencing soil loss rates of higher than 25 t ha^{-1} y^{-1} were enclosed and gullies protected, while the lower one was when areas with slopes of more than 25% were enclosed. The most effective way to reduce reservoir sediment deposition would therefore be to afforest areas experiencing high soil loss risk.

Application of management/conservation measures targeting areas experiencing soil loss rates of more than 25 t ha^{-1} y^{-1} and gullies could reduce the rate of sedimentation to about 25000 t y^{-1}, which is over 50% lower than under the existing rate. This can be achieved by excluding about 30% of the existing arable lands from cultivation. This implies the benefits of applying simple erosion/deposition models to identify possible sediment source areas and simulate possible management options that can reduce siltation before dam construction. The USPED model, which requires minimum data but simulates gullies well and estimates net soil losses from catchments, can thus be used as a preliminary tool to predict siltation problem of potential dam sites before construction. This could reduce investment losses due to quick siltation of dams as well as increase the benefits of the water harvesting schemes.

Generally, the results show that to achieve a reasonable decrease in reservoir sediment deposition, a relatively large decrease in the proportion of cultivated and open grazing lands may be required (except for the case of gullies). This may not be acceptable considering the already small plots of land owned by farmers in the study area. The decrease in arable land should, therefore, be accompanied by an intensification of the remaining cropland and by an increase in the benefits of the proposed area enclosures. Since it takes time before the new land use can start to benefit the farmers, the government may need to consider mechanisms of compensation to make the change economically feasible for farmers in the short term, until they are able to derive goods and services from the enclosures.

The study demonstrates the usefulness of soil erosion/deposition modelling as a tool for optimizing land use and management strategies to reduce reservoir siltation in the Ethiopian highlands. The modelling system also enables the results of proposed land management options for reducing sediment to be tested without undertaking basin-wide monitoring programs, which are generally much more expensive and time consuming. However, more research will be needed to validate the simulation results with actual field measurements. The results should, therefore, be used to assist decision support rather than to provide precise management guidelines. The simulation results could provide insight into what *might* happen, but they can not tell what *will* happen (Hessel et al., 2003). The simulation results also offer the possibility to select the most effective scenario from the perspective of net soil loss/sediment yield reduction. However, the cost-effectiveness of each scenario needs to be determined by balancing the benefits acquired from the implementation of the conservation measures with those lost due to the exclusion of arable/grazing land from their current use.

The fact that the USPED is not purely a sediment transport model might have an effect on associating net soil loss from catchments with annual sediment deposition in reservoirs. However, since the soil loss prediction by the model showed very strong correlation with annual sediment yield estimates, its application for simulating sediment yield reduction due to different management scenarios could be acceptable. Its application is attractive as it simulates soil loss from gullies and requires minimum data. Its accuracy may, however, need to be tested with more data and calibrated for any deviations, if its net soil loss predictions from catchments are to be strictly associated with sediment deposition in reservoirs.

8 SUMMARY AND CONCLUSION

This chapter gives concise summery of the results of the study with respect to the four main objectives. Figure 8.1 summarizes the major tasks, approaches, results and implications of the results. Further research needs and policy implications are also highlighted.

8.1 How severe is the siltation problem?

The very starting point to appreciate the problem and prioritize areas of intervention is to know the magnitude of the problem, in this case reservoir siltation. Even though the reservoir siltation problem is recognizable from field evidence and interviews, quantitative information is necessary to support government plans and decisions. Reservoir surveys were conducted to achieve this goal and the siltation rates of 11 reservoirs were estimated. Results show that sediment deposition ranged between 3 and 49 t ha^{-1} y^{-1}. The mean annual rate of sediment deposition was about 19 t ha^{-1} y^{-1} with a median rate of 11 t ha^{-1} y^{-1}. With this rate of siltation, most of the reservoirs lost more than 100% of their dead storage capacity within less than 25% of their anticipated service time. Using the sediment deposition data, it is possible to identify sites that require immediate conservation measures more than others. For instance, the reservoirs Adikenafiz, Gerebmihiz, Grashito, Gindae and Maidelle require sediment flushing or dredging, because their dead storage is lost and/or their spillway is blocked with sediment. Most of the sites also require urgent catchment conservation, as the potential for siltation due to terrain, lithology, surface cover or gullies is high. With the reservoir survey data, the following questions can be answered: How severe is the siltation problem, and which sites in the region require prior attention relative to others?

8.2 What are the determining factors of siltation?

Reservoir siltation is a function of catchment attributes, both anthropogenic and geomorphologic. Each site has its own unique attributes, whose interaction could result in different types of erosion/deposition processes and soil loss/siltation rates. The wide ranges in the sediment yield of catchments can be attributed to differences in their environmental attributes. Assessing the correlation between annual sediment yields in reservoirs against the corresponding environmental attributes of catchments enables understanding of the role of single and combinations of factors and evaluating which factors play the most important role. Statistical and principal component analyses results show that gullies, surface lithology, height difference and LUC types play predominant roles in controlling sediment yield variability. Generally, reservoir siltation was high for sites where pronounced terrain, erodible lithology, poor surface cover and a dense network of gullies coincided. This step of the analysis thus made it possible to answer the question: Which environmental attributes of catchments affect sediment yield variability and therefore need prior attention to reduce siltation?

8.3 Where are the major sediment source areas?

Knowledge of the factors that enhance erosion/siltation may not be adequate to tackle the problem through conservation/management measures unless the landscape positions of the key factors that control sediment yield are properly identified. This calls for approaches to identify the location of hot-spot areas that are important sources of sediment. This is a necessary step, because not all areas of the catchments can be conserved for financial and practical reasons. It may also not be feasible to invest resources to conserve sites that are not contributing significant amounts of sediment to the reservoirs. GIS-based spatially distributed models were used to map the spatial pattern of erosion/deposition within the catchments and identify areas with a high risk of soil loss. The maps were then classified into different soil loss categories, and landscape positions experiencing soil loss rates higher than the acceptable threshold were flagged as those requiring urgent conservation intervention. Generally, landscape positions where elevation is high and slopes are steep, surface cover is poor or the network of gullies is dense experience higher soil loss rates than others. This step therefore made it possible to identify landscape positions experiencing high soil loss and ultimately answer the question: Where does most of the sediment come from?

8.4 What is the appropriate solution to reduce siltation?

Once the important factors controlling siltation and the major sediment source areas are known, the next step will be to determine what type of conservation activities can be adopted to reduce soil loss and downstream delivery. Since the sediment delivery ratio

(SDR) is generally high in the region, there will be a higher probability that an eroded soil is delivered to an outlet. Protection of upslopes would, therefore, be a better option to reduce downstream sedimentation. It has also been observed that off-site-based measures play no significant role in reducing off-site delivery of sediments (Verstraeten et al., 2002b). The conservation activities targeting hot-spot areas could, therefore, be beneficial to reduce upstream erosion and downstream siltation. In this study, different LUC-redesign scenarios were simulated to assess their effectiveness in reducing soil loss. Major areas that contribute high amount of sediment such as gullies, steep slopes and areas where natural attributes and human activities lead to high erosion (hot-spot areas), were targeted during the simulation. The simulation results show that targeting hot-spot areas of erosion such as gullies and those experiencing a soil loss of more than 25 t ha^{-1} y^{-1} results in a significant reduction of sediment yield (over 65%) compared to the current condition. This intervention could increase the productive life span of the reservoirs by over 50% compared to the current trend. This demonstrates the need for catchment rehabilitation and afforestation before and after the construction of the water harvesting schemes, if their services are to be sustainable and cost effective. The hot-spot area-targeted scenarios ultimately allow identification of an appropriate location where conservation practices could help to reduce soil loss/sediment yield to an acceptable level. The analysis at this step therefore made it possible to answer the question: What conservation measures placed where are more efficient?

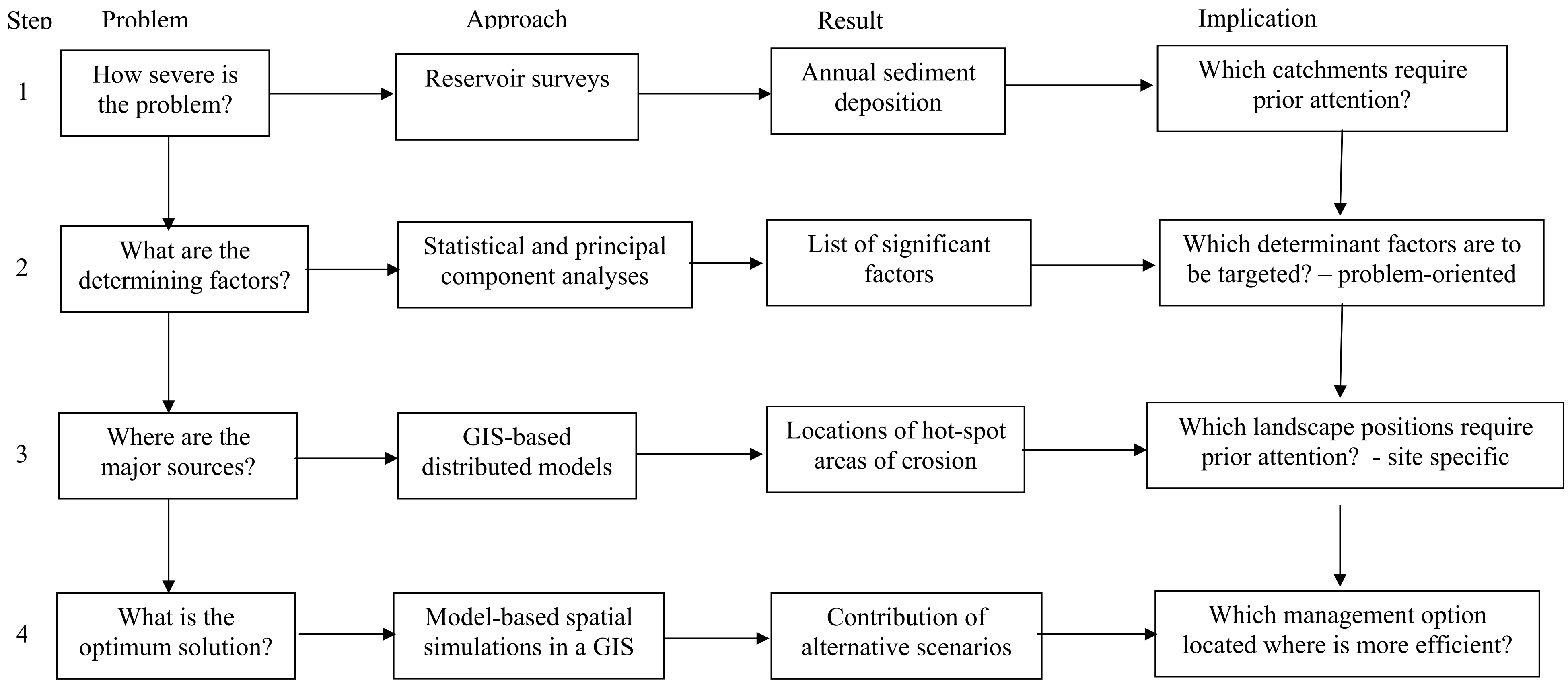


Figure 8.1: Procedures employed to fulfil the objectives of the study

8.5 Research and policy implications

The reservoir siltation analyses conducted in this study could provide relevant information for planners and decision makers. It also serves as a basis for further study. Major research and policy implication are outlined below.

- The 11 reservoirs for which sediment yield estimates were performed are representative of catchments in the region. However, additional data for a larger number of reservoirs is necessary to account for the heterogeneity of catchments in northern Ethiopia. These data could help to establish an appropriate predictive equation for planning purposes, which would reduce the necessity of conducting sediment yield estimations on a more frequent basis.
- Soil erosion models can serve as important tools to predict the rate of soil loss and evaluate patterns of erosion/deposition. Currently, our understanding of erosion processes is high, and there are several models to predict soil loss. However, the accuracy of model results is highly influenced by the input variables used. Calibration and validation of distributed models is also difficult due to limitations in data availability, especially when models are applied on a catchment scale. In such circumstances, it is recommended to use the models as tools for pattern recognition rather than for estimating “absolute” soil loss rates.
- The models applied in this study are not specifically calibrated for conditions in the study area. The soil loss rates estimated in this study could, therefore, be representative of the average conditions in Ethiopia, as the rainfall erosivity (*R*), soil erodibility (*K*), cover-management (*C*)and support practice (*P*) factors are based on adaptations made for the country. In order to obtain region-specific soil loss rates, it is necessary to calibrate the models taking the local conditions of the region into consideration.
- Field evidence, the ranking and scoring approaches and the Unit Steam Power-based Erosion/Deposition (USPED) model results show that gullies play a crucial role in the siltation of reservoirs. However, quantitative field data and detailed analysis is needed to determine the rate of soil loss contributed by gullies and the relative contribution of other sources in order to design appropriate management plans for specific processes and locations.

- Catchment erosion is responsible for reservoir siltation. However, the link between the two will not be similar for all sites due to differences in the types and extents of intermediate storages. The sediment delivery ratio (SDR) is an important parameter that dictates the link between catchment erosion and downstream sediment delivery. It affects the rate of siltation and the necessity and location of management measures. It is, therefore, necessary to conduct detailed research to quantify the volume of intermediate storages (SDR) of the catchments and to understand the main governing factors.
- This study shows that while there are sites with high siltation rates, there are also sites with relatively low siltation rates. Most of the sites with high siltation are located at the junction of collapsing gullies and below geomorphologically active areas. Careful site selection is, therefore, an important component of an overall water harvesting strategy. Merely focusing on the construction of a large number of dams may ultimately result in resource wastage instead of benefits.
- The scenarios simulated in this study demonstrate that enclosing erosion risk areas could reduce sediment yield significantly. However, afforestation of upslope areas may reduce agricultural land and influence farmers' livelihoods. Strategies, therefore, need to be devised in which the involved farmers are compensated or can share the benefits from intensified land use downslope. Since the enclosed areas could provide services such as sources of livestock feed, construction materials and the like in the long-run, compensation and incentives may help to satisfy the short-term needs of the farmers. In addition, agroforestry systems could be introduced in those areas which are designated to be enclosed so that the farmers can produce crops, while at the same time erosion and its downstream delivery will be reduced. In the upslope areas where erosion is high, crops with good surface cover, which can retard erosion, could also be cultivated to minimize the possibility of land shortage.

- Unless the farmers living upslope of the dams are given a share in the benefits downslope, conservation activities will not be sustainable. Farmers will not be interested in conserving the catchments, if all the benefits go to downslope settlers. This is even more important when dams are built below watersheds governed by two or more administrate units. This was experienced in some of the sites where interviews with farmers who own cultivable and grazing land upslope of the dams but who live in different administrate units showed no interest in participating in conservation activities. They were also not interested in maintaining broken terraces, as they considered that such activities are meant to benefit those who irrigate their lands far downslope. There is, therefore, a need to devise mechanisms to allow upslope settlers to share benefits with those who live downslope so that they will actively participate in conservation practices and avoid practices that enhance degradation and erosion.
- There is no question that water harvesting is one option to improve the food security of the population and satisfy the increasing demand for water by different sectors. However, siltation due to catchment erosion will remain a critical challenge to the water harvesting schemes. Before water harvesting schemes are installed, it is, therefore, important to study the erosion-siltation potentials of the catchments, determine the possible sediment source areas and simulate the efficiency of different management activities in reducing soil loss and its potential delivery. Construction of dams merely based on a preliminary field survey for site selection could have a much higher negative impact than the short-term benefits from the reservoirs. It is, therefore, crucial to conduct such studies using simple erosion models in a GIS before dam construction, so that there will be no unnecessary resource wastage by building dams at locations where they will not give the envisaged benefits.

- Northern Ethiopia is one of the most degraded regions in the world. People are cultivating fields that have almost lost their top soil and the returns are very low. Rainfall is very unreliable and subsistence farmers are the most vulnerable. In such environments, detailed accounting of resources, potentials and constraints is necessary for planning and management purposes. There is, therefore, an urgent need to conduct detailed study to characterize the region in terms of its productive capacities, ecological goods and services and conservation needs. Knowledge of the spatial pattern of the areas with such attributes could enable utilization of resources according to their potentials as well as prescribe relevant conservation measures targeted to specific locations and problems.

Erosion and its on- and off-site effects will remain one of the major challenges of agricultural productivity and water harvesting schemes in Ethiopia. Planning for management and conservation activities requires data on the severity of the problem and its spatial pattern. Evaluation of the possible impacts of different conservation activities are also vital to support decision making. The results of this study could serve as an important benchmark to develop tools to aid prioritized and site-specific conservation measures of catchment management.

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ACKNOWLEDGEMENTS

My heartfelt gratitude to Prof. Dr. Paul Vlek for giving me the chance to join ZEF for my PhD study and his excellent scientific advice during the whole course of my work. I also benefited a lot from his immense experience during his visit to my field sites. I am very grateful for his full support not only in the area of academics but also administrative wise. His patience, understanding and readiness to help are extraordinary. I very much thank Ass. Prof. Soojin Park for his constructive advice, valuable discussions during my field work and his friendly approach. I also thank Prof. Dr. Richard Dikau for the enormous discussions we had and his constructive advises. I very much thank Prof. Dr. Armin Skowronek and PD. Dr. Christopher Martius for their willingness to be members of the Examination Committee.

I thank the DAAD for supporting my PhD study and providing me with field support. I also very much appreciate their understanding to fund my travel to go home to visit my parents after my Fathers' death. I am grateful to ZEF for supporting my field works. I also thank Mekelle University for hosting me during my field research and providing me with transport facilities. I thank the Ministry of Water Resources, Addis Ababa, for the help to carry out the bathymetric surveys. Special thanks to Mr. Deksyos for organizing the mission and Mr. Kaleab and Mr. Mohammed for carrying the bathymetric survey.

My heartfelt thanks goes to my dear wife Tsedale Kebede and our lovely sons Robel and Nahom for being patient and accommodative while I was away in Bonn as well as in the field. With out their support and strength, I may not have accomplished my work successfully.

I would like to express my thanks to all staff members of ZEF. Special thanks to the ZEFc secretariat (Sabine Aengenedt-Baer, Andrea Berg, Miryam Schneider) who are always helpful and cooperative. Many thanks to Dr. Günther Manske, Rosemarie Zabel, Hanna Peters, Dr. Mathias Braun (ZFL), Volker Merx, and Ludger Hammer for their immense support in various administrative and technical issues. I would like to mention Mrs. Zabel´s extraordinary help related to accommodation in Bonn and registration into the Faculty. I also thank Margaret Jend for editing my English and translating the German abstract. I am very thankful to Frau H. Franz (Mathematisch-Naturwissenschaftliche Fakultät) for her assistance and patience when I was asking her many questions related to the new regulation.

I thank Dr. Adrian Chappell, Leeds University, for his comments on my proposal, and enormous discussions related to caesium-137. I also thank Dr. Eric Craswell for reading portions of my draft Thesis.

I would like to extend my deepest thank to colleague Quang Bao Le for being very good friend and the several inspirational academic discussions we had since the beginning of our ZEF life. I also thank Carme Costa for her devoted support during field work and also for digitizing maps as well as editing GPS points. I thank Almut Brunner for sharing materials and being very sociable friend.

I am very grateful to all Ethiopian students in Bonn (Mekuria Argaw, Teklu Tesfay, Samson Kassahun, Tsegaye Yilma, Abay Asfaw, Admassu Shibru, Feyera Senbeta, Degnet Abebaw, Dilnesaw Alamirew, Dawit Tesfay and others) for their friendship and support. I would like to especially mention Mihret Demissew for her all-round support with her extremely nice Ethiopian socio-cultural charisma. I have gained tremendous support from her which I will never forget. I thank Daniel Tsegai for being very good friend to me and to all Ethiopians. I am also thankful to Kavita Rai, Prasnee Tipraqsa and Cristina Carambas who remained close friends since we met 4 years ago.

My special thanks also goes to Assefa Abegaz for his enthusiastic support in different aspects. He was very instrumental in my work related to soil pit descriptions and reservoir pit data collection. I also appreciate all the ups and downs he has experienced to encourage me during my difficult time. I also thank Kifle W.Aregay for his friendship and the interesting discussions related to surface lithology and its erodibility. I thank staff members of Mekelle University, mainly, Dr. Mintesinot Behailu, Dr. Fasil Kebede, Ermias Aynekulu, Amanuel Zenebe, Yohannes Alemseged, Selamawit Girmay, Lemlem Berhe, Lia Amare, Teklay and Berhe (transport office) for their help in various circumstances. I also thank my field assistants Hailu Girmay, Tsehaye Yigzaw and driver Amanuel Assefa for their honest and devoted work during our long field stay. My thanks also goes to the staff members of the Mekelle Bureau of Water Resources. I also thank the Woreda and local officers in Tigray who facilitated my field work. I am grateful to the Hintalo, Adigudom, Enderta and Laelaywukro farmers who were very kind and supportive of my field work.

I am very grateful for my long time "English parents", Eileen and Derek and the whole family and my friend Mikael Black.

Finally, I acknowledge the contribution of my father Tamene Desta, my mother Alemitu Kassa and my brother and sisters, who helped me all the way through my academic career. I am especially indebted to my late father Tamene Desta, who was the key for every step of my success.