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%.

[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).

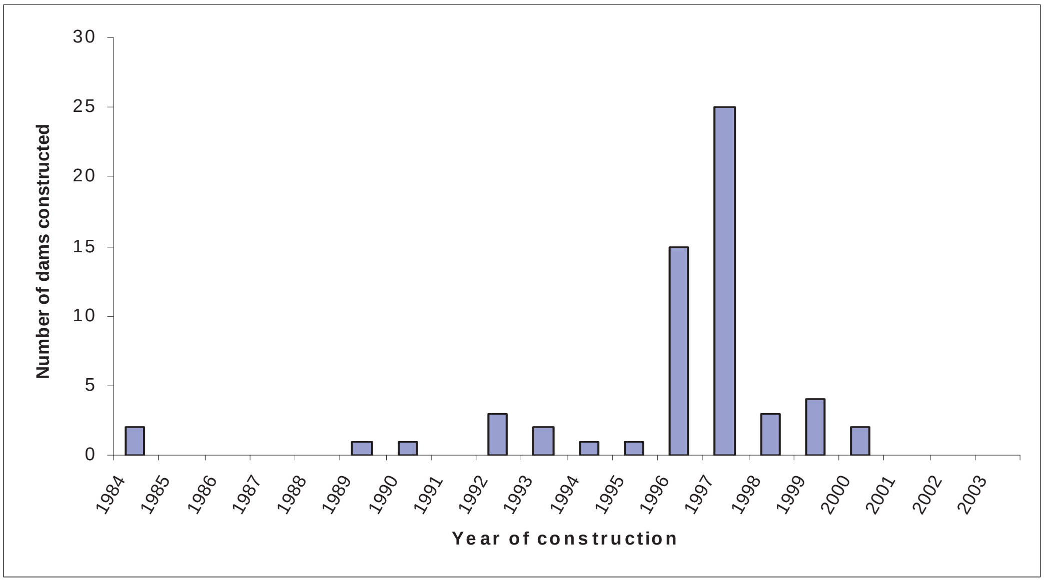

Figure 2.1: Number of micro-dams constructed in Tigray, N. Ethiopia by year. The dams' capacities range from 3.10 $*10^6$ m^3 to $0.11*10^6$ m^3 and a height of 9 to 24 meters. In an international context, the dams can be classified as small to medium size[3] (Source: CoSaERT unpublished reports)

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.

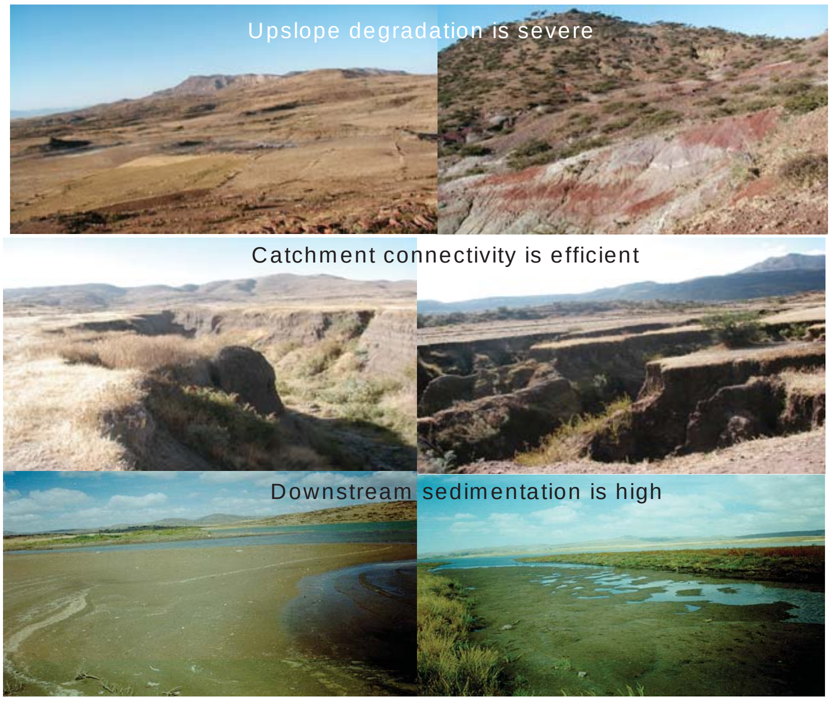

Figure 2.3: Severity of erosion and siltation in Tigray. Mountainous and slopy terrain, poor surface cover and steep slope cultivation, deep and wide gullies of high density are major characteristics of the region

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).