8 Discussion

8.1 Rainfall-Runoff

Analysis of both rainfall and runoff is rudimentary as only little spatial and temporal data are available. Moreover, rainfall and runoff data do not overlap in time. Significant gaps in the obtained time series allow no or only very coarse rainfall-runoff analysis.

8.1.1 Rainfall

The inter-annual precipitation variability analysed in the research area coincides with observations from OSMAN (2001) or SELESHI & DEMAREE (1995) in the Ethiopian Highlands. Also HURNI (1982) describes high inter- as well as intra-annual precipitation variability in Ethiopia. SELESHI & DEMAREE (1995) notice only a weak correlation of precipitation variability to the Southern Oscillation Index. However, warm ENSO events seem to match with years of below average rainfall, particularly for the main rainy season in June to September. GREGOR (2002), in his research on linkages between vegetation cover (NDVI) and climate variability, also found only a weak correlation between ENSO events and and changes of vegetation cover. MORON ET AL. (1998) describe three inter-annual oscillations in sea-surface temperatures for the tropical eastern Pacific, of which only one (60-65 year period) extends through the whole Pacific. As precipitation in Ethiopia is strongly linked to the movement of the ITCZ (OSMAN, 2001) and the influence of the Indian Monsoon (KRAUER, 1988) sea-surface temperatures of the Pacific have a strong influence on the availability of water vapour in the local atmosphere. Thus, the oscillations observed by MORON ET AL. (1998) give some additional insights on the precipitation dependence on global sea-surface temperatures. NICHOLSON ET AL. (1997) describe the high inter-annual variability of rainfall in Africa and general trends of rainfall amounts: during the last few decades a general trend towards drier conditions is modelled in their study for Africa. NICHOLSON (1994) and MORON (1998) observed similar patterns. However, time series of rainfall data in the research area are not long enough to allow meaningful conclusions.

Different causes of inter-annual variability are not discussed in detail, as long-term changes are not of major interest in this study. However, the effects on climate change and variability due to the sunspot numbers, the depletion of the ozone layer as well as the effect of greenhouse gas are known and have been discussed in detail elsewhere (GASSE, 2000; THOMPSON, 2000; MAYEWSKI ET AL., 2004; ADAMS & PIOVESAN, 2005 and MENDOZA, 2005).

The intra-annual precipitation variability in the area is high. Annual time series of monthly rainfall totals display an alternating pattern of dry and rainy seasons for all rain gauging stations. BEKELE (2001) as well as GREGOR (2001) highlight similar results. More research on intra-annual precipitation has not been carried out in this area. NYSSEN ET AL. (2005) show high intra-annual rainfall variation for the Ethiopian Highlands of northern Tigray.

Daily rainfall patterns can be explained by the dominance of convective rains due to the Earth's surface heating in the morning hours (NYSSEN ET AL., 2005). Since detailed information on precipitation totals, such as hourly data, is not available in the *Bilate* watershed, verification using local data is not possible. Results of studies carried out in one part of the country cannot be easily transferred and compared to other parts. . However, diurnal convective rainfall events are dominant in the *Bilate* watershed, but temporal and spatial variability cannot be analysed due to the missing data. NESBITT & ZIPSER (2002) observed the diurnal rainfall cycle: precipitation has its minimum in the morning hours and a maximum in the early afternoon and evening. Meso-scale convective systems have their intensity peak in the late afternoon, decreasing to midnight. The same rainfall pattern was experienced in the research area during fieldwork.

Rainfall is generally dependant on altitude (PRUDOMME, 1999). BEKELE (2001), KRAUSE ET AL. (2004) and THIEMANN & FÖRCH (2005) also observed vertical precipitation patterns in the area of the Lake Abaya-Chamo Basin. However, the relationship varies throughout the year: no or only weak correlation between altitude and precipitation could be detected in the dry season (October to January), but the correlation is significant during the rainy season (February to September). This excludes the month of April which represents the time between the short and long rainy season. Correlation is also weak here. GOOVERTS (2000) included altitude into the spatial prediction of rainfall in a mountainous region in Portugal. For two month in summer time (dry season) he calculats the correlations of 0.33 and 0.39, respectively, whereas during months of mean rainfall >10 mm the correlation ranges between 0.69 and 0.83 and for the annual average the correlation is 0.79 (n=36). His explanation for the increase of precipitation with increasing altitude is the orographic effect that causes condensation of the air masses due to adiabatic cooling. HEVESI ET AL. (1992a, 1992b) also calculate a significance of 0.75 between average annual precipitation and altitude for 62 stations in Nevada and south-eastern California.

Both, GOOVERTS (2000) and HEVESI ET AL. (1992b) observe a better correlation between monthly precipitation and altitude during the rainy or wetter season of their research area. In contrast, the mean absolute error was higher in the wetter month than in the drier month (GOOVERTS, 2000). Similar patterns were observed in this research and comparisons of the distribution of monthly average precipitation show that the dependence on altitude is more pronounced in the rainy than in the dry season.

Rainfall events in the watershed are mainly of short duration and high intensity. No previous research on rainfall intensity has been carried out in the southern Ethiopian Rift Valley and rainfall intensity data for durations smaller than one hour are not available. Comparison of field observations (qualitatively) in the *Bilate* watershed and measured rainfall intensities in northern Ethiopia show similarities, even though the different rainfall regimes of both areas are known. NYSSEN ET AL. (2005) account 88% of rainfall events as having intensities smaller than 30 mm/h. In general, high intensities have short durations and the diurnal rainfall pattern is explained by the dominance of convective rains. Intensities in the watershed are expressed exemplarily with data of one meteorological station. Here, rainfall events are local storms of short duration (1-5 h) and high intensity up to 30 mm/h (THIEMANN & FÖRCH, 2005).

Since detailed rainfall intensity data are not available for the watershed and its surrounding, a rainfall-intensity-index (RII) was designed for this study. The RII was calculated in a first step for each single meteorological station and subsequently interpolated to spatial data using the kriging method. GOOVAERTS (2000) finds the simple kriging method best for predicting spatial precipitation in mountainous regions. Also PRUDOMME (1999) utilizes the ordinary kriging method for compensating the lack of data by the spatial estimation of rainfall in mountainous areas of Scotland. Both superimposed the kriging method on multivariate geo-statistical algorithms for incorporating a digital elevation model into the spatial estimation of rainfall. Thus, utilizing these methods of rainfall estimation seems to be feasible.

VAN DIJK ET AL. (2002) critically review published studies of rainfall intensities and kinetic energy with the aim to derive an exponential equation to make general predictions. USLE approaches to obtain a rainfall erosivity factor seem not to bee warranted and standardised measurements are needed to evaluate rainfall intensity. However, these measurements were never carried out in the Lake Abaya-Chamo Basin. LAL (1998) measured energy loads, drop size distribution and related it to rainfall totals and intensity in Nigeria.

Frequency for high medium drop size was higher for rainstorms in March, June and September, than in the other months. Medium kinetic energy (1000-2000 J/m²) was measured in July and August and high kinetic energy (>2000 J/m²) in May and September. Lower energy was common in the other months (LAL, 1998). His results match qualitatively with observations in the *Bilate* watershed. In this research, rainfall intensities are determined using the rainfall intensity index and show the highest values during the transition period between rainy and dry season as well as during the dry season. However, this index represents rainfall intensity of rainfall totals but it does not consider energy load, which also depends on drop size.

8.1.2 Runoff

The runoff analysis of the *Bilate River* is limited because of poor data availability and data quality. However, the discharge volumes at all river gauging stations show an intra-annual bimodal distribution. BEKELE (2001) compared discharge of the *Bilate River* at two gauging stations and also identifies a bimodal distribution of discharge totals. But these are of little meaningful character due to lack of data and inappropriate data comparison. SCHÜTT ET AL. (2002) report the same distribution.

The inter-annual monthly maxima and minima discharge volumes do not always occur in the same month. Since discharge depends on precipitation totals, evaporation and water storage, precipitation variability causes high discharge particularly in rainy season, when soil is saturated and evaporation is less than in the dry season due to higher cloud cover (LEGESSE ET AL., 2003). Research conducted by LEGESSE ET AL. (2003) identifies the sensitivity of water resource changes due to climate variability in the Rift Valley Lake Region. There, the general climatic conditions are very similar to those observed in the Lake Abaya-Chamo Basin. The mean surface water balance reported by LEGESSE ET AL. (2003) is of high inter- and intra-annual variability, consistent with observations in the *Bilate* watershed in particular and semi-arid to humid African landscapes in general (NICHOLSON ET AL., 1997).

Average discharge volumes of the rainy season calculated for the river gauging station *Batena* are much higher than those of other gauging stations, even though its watershed is much smaller. Although precipitation totals are expected to be high due to the higher altitude of the watershed, it is unlikely that they cause the reported runoff. It seems that measurement failures, such as wrong measurements of the water level, wrong or not adapted rating curves, are the likely cause of the high readings. The possibility of assessment failures is quite high (WHALLEY ET AL., 2001). However, the 1992 discharge volumes of the *Batena* gauging station do fit to the corresponding precipitation volumes and can therefore provide some insights.

8.1.3 Rainfall-Runoff

The rainfall-runoff analysis shows a direct correlation between runoff and precipitation totals. THIEMANN & FÖRCH (2005) estimate a time lag of approximately one month between maximum rainfall totals and maximum discharge for the *Bilate Tena (Dimtu)* gauging station and its drainage area. This time lag is only valid for the time period from dry to rainy season. Here soil moisture is initially low and saturation of the soils is just starting. Thus, interflow does not yet occur. During the rainy season interflow and overland flow are fully active and no time lag between maximum rainfall and maximum discharge is evident.

In this study, detailed research on rainfall-runoff interactions was not carried out. BEKELE (2001) provides a rough overview for the Lake Abaya-Chamo Basin. Evaporation or infiltration data, as well as detailed soil data hardly exist and thus, scientific analysis requires a considerable data assessment that is not the focus of this study. TILAHUN (2006) analysed potential evapotranspiration for the Rift Valley Lake Region and the central Ethiopian Rift Valley. His results coincide with the estimation of evaporation done by BEKELE (2001). However, standard methods for estimating potential evapotranspiration, such as from HAUDE (1955), THORNTHWAITE & MATHER (1957) or PENMAN (1956) require detailed meteorological data, which are not available in the Lake Abaya-Chamo Basin. Moreover, these approached are partially of empirical character and have been developed in moderate climates or for special vegetation cover. Transformation of these formulas to tropical regions must generate uncertainties. The best method seems to be from THORNTHWAITE & MATHER (1957), since it utilises monthly values and large-scale areas (DVWK, 1996). The transformation of the results of BEKELE (2001) to the *Bilate* watershed show, that annually only ¼ of the precipitation volumes is draining and ¼ is evaporating (THIEMANN & FÖRCH, 2005). However, the components of the water balance are in part inconsistent. In particular, precipitation volumes are more than 20 times higher than discharge volumes during the dry season, whereas this relationship is more balanced during the rainy season.

Rainfall-runoff correlations of the river gauging stations *Guder, Batena, Weira* and *Alaba Kulito* show similar problems. Especially the small watersheds upstream of *Guder, Batena* and *Weira* show a high discrepancy between rainfall and runoff volumes. Here, short time series, gaps in the time series and missing meteorological stations might explain the inconsistent results.

8.2 Erosion- and Soil Erosion

The erosion and soil erosion damages observed in the eight selected watersheds show highly variable forms and extents. Causes of erosion and soil erosion have been generally discussed in chapter 3.2. In this section, the environmental conditions that cause the erosion and soil erosion damages occurring in the watershed and study sites are discussed. Focus of the discussion is on:

- specific location of the damages
- horizontal and vertical extent of the damages
- influence of geology, soil type / soil property, relief and precipitation on the damages
- influence of human activities that cause or prevent damages
- scale of the damages relevant for modelling and / or decision makers and farmers, respectively

Five major forms of erosion and soil erosion damages have been detected during the field assessment resulting from:

- sheet erosion (inter-rill erosion)
- rill erosion
- gully erosion
- badland erosion
- degradation of barren land

8.2.1 Sheet Erosion

Sheet erosion and inter-rill erosion are the results of splash effects and can therefore occur anywhere where precipitation occurs. It is a natural effect, which is enhanced or restricted by land and vegetation cover. Both can partially shield the soil from the splash effect (HOGG, 1982). As most of the soils in the *Bilate* watershed are of high to very high clay content, the splash effect has to be considered carefully. Rainfall drops pounding on dry soil at the beginning of a rainfall event cause significant rain splash damages. Unconsolidated material is hereby heavily affected. Later, clay in the topsoil swells and starts to develop an impermeable layer that protects the subsurface from erosion (RUY ET AL., 1999).

In addition, the unconsolidated material of the surface is levelled and consolidated by the rainfall event at a micro-scale, and thus the splash effect reduces the erosion and soil erosion vulnerability. Surface water will now accumulate and decrease the energy transmitted by the raindrops. Simultaneously, surface runoff starts. However, raindrop diameters measured in the Northern Ethiopian Highlands during convective rainfall events are very large and therefore strongly impact the ground (NYSSEN ET AL., 2005).

The two effects therefore cause sheet erosion and inter-rill erosion but also prevent it. Indirect indicators for sheet erosion have been detected within all study sites in the watershed. Different levels of soil losses are indirectly represented through different heights of tillage edges or different extents of off-site damages (such as fans). The estimation of soil loss volumes due to sheet erosion is very complex and thus, not feasible for usage as an input factor for the model being developing in the research. Damages caused by sheet and inter-rill erosion respectively are therefore neglected. SCHÜTT & THIEMANN (2001) detected indicators for sheet erosion across different study sites in the Ethiopian Highlands. However, they did not account for this erosion form in their erosion and soil erosion risk model due to the limited available information on processes causing sheet erosion in that area.

8.2.2 Rill Erosion

Whenever surface water runoff starts, rill erosion takes place (GROSH & JARRET, 1994; EDWARDS ET AL., 1995). In the *Bilate* watershed rill erosion is causing severe damages next to gully erosion, the development of badlands and degraded areas. But in contrast to damages from gully erosion, the damages from rill erosion are not visibly obvious at all times. Rills develop throughout the rainy season on all agricultural fields, but are levelled during the dry season by livestock trampling and at beginning of the following rainy season by ploughing. However, ephemeral rills constantly develop during each rainfall event and are temporally independent from rainfall regimes. Due to the high clay content of all the soils occurring in the watershed, rainfall rapidly generates Horton overland flow (RUY ET AL., 1999) during the dry season and saturated overland flow during the rainy season. The exceptions are areas of Vertisols, where soil surface cracks tremendously increase the infiltration capacity during dry season. Overland flow can also take place as long as clay minerals swell and seal the surface layer (CHAHINIAN ET AL., 2005).

Rills have been detected in great numbers in the *Western Ethiopian Highlands* on agricultural fields and within different relief elements. Dominant factors causing these damages here are land use and vegetation cover, as well as precipitation totals and intensities.

Soil type and geology are of minor cause, whereas gradients of slopes, slope length and relief curvature strongly influence the development of rills.

In fact, in the *Western Ethiopian Highlands* rills develop independently of the soil types. However, the frequency and magnitude of rills seem to be higher on Nitisols than on Leptosols. Leptosols only occur on volcanoes (FAO, 1998) and here the relief is different: slope lengths are shorter and relief curvature is gentler than in the *Western Ethiopian Highlands*. This differentiation is more of qualitative than of quantitative character. However, rills in the *Western Ethiopian Highlands* reach maximum depths of 20 cm. This has historical reasons: agriculture has a long tradition and during at least the last 2,700 years farmers used the same traditional plough called *Maresha* (GEBREGZIABHER ET AL., 2005). This plough aerates the top 20 cm of the soil only; trampling from oxen which are pulling the plough as well as from common livestock grazing during the dry season compact the soil and develop a plough pan at a depth of approximately 20 cm (GEBREGZIABHER ET AL., 2005). This plough pan is more or less impermeable due to its high compaction and chemical reactions, which lead to formation of very clayey layers. This chemical transformation develops clay minerals, predominantly kaolinite which rapidly swells in contact with water (RUY ET AL., 1999). In addition, weathering of clay minerals occurs and allophone could develop (BRONGER, 2000). The plough pan prevents further infiltration of surface water and thus, the topsoil saturates rapidly. Once the resistant threshold against mudflow of the topsoil is overcome, it starts flowing on very steep slopes. This process also tremendously increases the development of rills on flatter slopes (HOGG, 1982; GROSH & JARRETT, 1994; VAN LIEW & SAXTON, 1983).

The damages caused by rill erosion are different across the study sites because they also depend on the ploughing method. Whereas contour ploughing is known at the study site *Hage,* the other sites are ploughed conventionally. In *Hage (WEH)* only few rills develop throughout the rainy season and some of the larger rills seem to be permanent and inactive. The magnitude and frequency of rill erosion is higher at similar slope gradients in the study site *Ana (WEH)* where farmers are ploughing conventionally.

Measurements of the magnitude and frequency of rills as an indicator for calculating soil loss on a test plot resulted in approximately 0.8 cm soil loss for a single storm event. This rainfall event (17/08/2002) was recorded at the meteorological station *Fonko* with a total of 23 mm/day (2002: mean=3.8 mm/d, SD=7.2, max=42.8 mm/d, n=356). BEWKET & STERK (2003) calculated an average soil loss of 4 mm per annum for research plots in the north-western Ethiopian Highlands. These values of soil loss have to be considered carefully because soil loss is dependent on the force of both rainfall and surface runoff: intensities and amounts of precipitation differ between the study sites. However, soil loss due to rill erosion is severe in the *Western Ethiopian Highlands* of the watershed.

Gradient and length of slopes influence the water budget of topsoils. The longer the slopes are, the more surface water accumulates during rainfall events and thus, more energy is available for sediment detachment and transportation. The steeper the slopes are, the less energy from surface runoff is necessary to detach or transport material, as friction against gravitation is less (YAIR & RAZ-YASSIF, 2004). The magnitude and frequency of rills is strongly linked to these influences in the watershed. Long slopes, typified in this research by higher values of flow accumulation, cause bigger rills than shorter slopes, and steeper slopes lead to higher frequencies but smaller sizes of rills. BEWKET & STERK (2003) describe similar results from an assessment of rill erosion on agricultural fields in Ethiopia. Thus, the grades of damages from rill erosion depend predominantly on the length and gradient of the slopes. However, a quantification of the damages and soil loss is not presented in this research. Qualitative estimation during the field survey show no significant difference between soil losses from larger but rarely occurring rills and soil loss from frequent but smaller rills. However, larger rills are not ephemeral, as traditional ploughing is no longer levelling the micro-relief. Thus, these rills are more endangered by erosion and soil erosion than smaller ones. In addition, huge permanent rills often cause the development of gullies because surface runoff is converting and accumulating (HIGGINS ET AL., 1990; BILLI & DRAMIS, 2003).

Rills developed in the *Rift Valley* are generally of ephemeral character. Vertisols and Cambisols have high infiltration capacities at the onset of rainfall events that decrease rapidly due to the swelling of clay minerals. However, these wet soils exhibit very high adhesion and cohesion forces that prevent topsoil erosion (COUPER, 2003). Field studies in the eastern part of the Rift Valley discover layers of pyroclastic sediments of several decimeter depths, which have very high infiltration capacities. Here, an Andosol of high infiltration capacity also developed recently. In spite of short rainfall durations and high rainfall intensities in the *Rift Valley*, saturated overland flow occurs rarely and thus, the generation of rills is minor during the rainy season. But high intensities can cause Horton overland flow when the intensity is higher than the infiltration capacity. Both short rainfall duration and high intensity recorded for the *Rift Valley* are causing rill erosion damages, but not to a significant extent. However, the relief of the *Rift Valley* is of undulated and even characteristics and thus, slopes have small gradients. Surface runoff, whenever it occurs, has not the energy necessary to erode material over long distances (VAN LIEW & SAXTON, 1983). Rills in the *Rift Valley* are therefore insignificant, short and temporary.

In all geomorphological units, land use patterns and vegetation cover have a strong influence on the development of rills. In the northern parts of the *Valleys and Basin* the dominant land cover is grassland with an irregular pattern of trees and shrubs. This vegetation cover does not change throughout the year and is preventing soil loss from rill erosion. In contrast, the vegetation cover changes throughout the year in the southern parts of the *Valleys and Basin* (except the *Bilate Hayk Basin*), as well as in the *Western Ethiopian Highlands*. In times of high precipitation totals and high intensities at the onset of the rainy season vegetation is generally sparse or not existent, as farmers start ploughing the fields at the beginning of the first rain after the dry season (D'ANDREA ET AL., 1999) in order to increase infiltration capacity and thus, water storage. The aerated and bare soil is very vulnerable to soil erosion for a few weeks until seedlings start growing and roots systems start stabilising the topsoil. In addition, the distance between single plants is typically several decimetres (D'ANDREA ET AL., 1999) and thus, vegetation cover is not as high as it seems to be. After the harvest in the dry season, the vegetation cover is still relatively high, as crop residues are left on the fields for grazing livestock. However, rainfall is generally low during this time (November/December). Previously developed rills are now being levelled, as cattle roam across the fields in search for food. High rainfall intensities and short rainfall duration start again in January/February when cattle cleared all fields from vegetation cover. In summary, the extent of vegetation cover on agricultural fields is in general negatively correlated to precipitation totals and does therefore not shield the soil from sheet and rill erosion. Nevertheless, perennial vegetation cover from trees and shrubs protects soils as periods of growth coincide with the rainfall seasons.

In general, each single eroded rill has little effect on soil loss and therefore is not a significant indicator of erosion and soil erosion risk. But in an overall context, frequency and magnitude of rills typifies both, the quality of soil loss and the erosion and soil erosion risk. These causes for developing rills are therefore strongly considered in modelling, even though the damages from rill erosion in a short term context are of minor priority for farmers and decision makers, respectively.

8.2.3 Gully Erosion

Erosion and soil erosion processes causing gullies are well understood. However, gullies in the watershed are of varying shape and thus, the causes for the developments of these gullies were discussed separately for each geomorphological unit.

In the *Western Ethiopian Highlands* gullies are all v-shaped, independent of their dimensions. Often, the differentiation between the most recently developed gullies and gullies located in former natural drainages cannot be carried out. Development of gullies is often linked to the occurrence of footpaths, little maintenance of fields (such as levelling fields from bigger rills and small channels) and intensive utilisation of Eucalyptus plantations. In addition, gullies occur, wherever converting surface runoff exceeds a specific threshold. SCHÜTT & THIEMANN (2001) observed locations of gully heads predominantly on convex profile relief curvatures and on moderate to steep slopes throughout agricultural lands in northern Ethiopia. Gullies often develop, where surface runoff is captured by footpaths or road construction (HUDSON, 1995) or where soil conservation measures are badly maintained (HURNI, 1999). BOARDMAN ET AL. (2003) in historical review highlight some causes of gully development in South Africa: it is mostly anthropogenically induced. VALENTIN ET AL. (2005) show that gully erosion is dominantly triggered by inappropriate cultivation and badly maintained conservation measures. Also, TOY ET AL. (2002) explain the development of permanent gullies through the transformation of ephemeral gullies by tillage.

The geomorphological unit *Valleys and Basin* shows few gullies. Very high permanent vegetation cover occurs in the northern part, preventing gully development. In the southern part of the unit, tillage is dominating and thus, more gullies exist. The origin of these gullies is mostly captured surface runoff from roads and footpaths as explained by HUDSON (1995). THIEMANN ET AL. (2005) observe linkages between gully developments and captured surface runoff in northern Ethiopia.

Contrary to these v-shaped gullies of the *Western Ethiopian Highlands* and the *Valleys and Basin*, gullies in the *Rift Valley* typically have u-shapes cross-sections. Soil types in the *Rift Valley* are Vertisols, Andosols and Leptisols after FAO (1998). Soils of high and very high clay content under semi-arid conditions are vulnerable to gully sidewall processes, due to horizontal changes in soil moisture (MARTINEZ-CASASNOVAS ET AL., 2004). Rapid changes of swelling and shrinking lead to high aggregate instability and increasing development of cracks at sidewalls of gullies. Horizontal changes in soil moisture are increasing und thus, erodibility (COUPER, 2003). The content of Allophane is quite high in these soils in the watershed and clay minerals could only rarely be detected. The effect of clay swelling and shrinking is therefore likely, but its effects cannot be estimated, although 'shear strength of allophanic soils is less than in non-allophanic soils' (ALLBROOK, 1985). But in the *Rift Valley* a semi-permeable layer from volcanic sedimentation occurs beneath the topsoil layer at all locations where gullies are developed. This layer is protecting lower layers from erosion, but once eroded, broken or fractured (i.e. from tillage) the resistance of these layers diminishes. RUY ET AL. (1999) identify the reason for the porosity and erodibility of soils as the matrix as well as structural and macro-cracks. MARTINEZ-CASASNOVAS ET AL. (2004) verify the origin of gullies from variations in soil moisture content that influence shrinking and swelling of clay minerals and thus, the instability of the soils. Consequently erodibility increases and sidewall processes as well as hollow undercuts start.

The transition zone from the *Western Ethiopian Highlands* to the *Rift Valley* is characterised by gullies of v-shaped and u-shaped cross-sections. It seems that different cross-sections depend on different soils and soil properties, but this could not be verified in this study. One of the dominant factors influencing the cross-section shape is the occurrence of volcanic sediments. Their occurrence is more likely to cause u-shaped gully cross-sections. Additionally, slope gradients influence the design of gullies (HURNI, 1986).

8.2.4 Badland Erosion

Badlands occur in an irregular pattern in the *Western Ethiopian Highlands* and in the *Valleys and Basin*, whereas in the *Rift Valley* badlands are rare. In both the *Western Ethiopian Highlands* and in the *Valleys and Basin* badlands mostly coincide with the occurrence of Eucalyptus plantations or where the construction of roads or footpaths increases the gradient of slope to be steeper than the natural gradient. BOARDMAN ET AL. (2003) observe similar situations in the Karoo-Mountains in South Africa. The generation of badlands within Eucalyptus plantations is dependent, on one side, on the gradient of slopes where the forests have been planted, on the other side, on the age of the trees and the intensity of utilisation of the forest. Field surveys suggest that young trees can dominantly be found in 'closed areas', where cattle movement is forbidden. Forested areas are intensively utilised: livestock is grazing, leaves and branches are collected. Thus, ground cover is often missing and the surface is highly compacted by the impacts of livestock trampling. These compactions can initially cause the development of gullies and then badlands (BOARDMAN ET AL., 2003). The oily precipitation of Eucalyptus also disturbs the soil chemistry and in consequence also physical soil properties. Exchangeable anion capacity is decreasing under Eucalyptus plantations, as well as carbon, potassium and phosphorous (LEMENIH ET AL., 2004). Thus, the vulnerability of the soils to erosion increases. In contrast, on sodic soils, Eucalyptus plantations increase soil fertility (MISHRA ET AL., 2003). This phenomenon could not be verified in the research area. According to an interview with a teacher (see appendix 14.1, interview 4), badlands have existed in the *Valleys and Basin* for more than 40 years. It could not be determined, whether Eucalyptus trees have been planted on former badlands, or whether the badlands are caused by these trees. However, both always occur together. The exception is the occurrence of badlands parallel to roads, where construction failures cause erosion (SCHÜTT & THIEMANN, 2001)

In the transition zone to the *Rift Valley* badlands and huge areas of barren degraded land cannot be separately defined, whereas in the *Rift Valley* itself badlands occur very rarely. Here, the slopes at the rims of the degraded areas are very steep and the transition is distinct. COUPER (2003) explains that the clay content of the soils influences the stability of barren soils at the rims to degraded areas. SCHOLTEN (1997) expresses the low physical stability of the soil-saprolite complex in Swaziland. Observed erosion processes in the *Rift Valley* coincide with the results of SCHOLTEN (1997).

8.2.5 Barren Land Degradation

Erosion forms defined as ‘barren degraded land’ were only detected in the *Rift Valley*. No literature on this special topic could be obtained, and the discussion about the development of this form is therefore theoretical.

The observed erosion forms occur only parallel to rivers and only where profile curvature is convex and the slope gradient is greater than 2-3°. All erosion sites have a maximum depth of four to five meters and the bottoms are even. The rims towards not degraded areas are typically vertical and the horizontal extent of the erosion damage varies strongly. These erosion forms are always associated with the occurrence of volcanic sediments, which cover former developed soils. On top of these layers new soils develop. Geological maps from MOHR (1962) or FAO (1998) do not list the occurrence and origin of these volcanic sediments and its horizontal extent is therefore not determined exactly. Vertically, the pyroclastic layers range in depth from 20 to 50 cm. However, these layers are semi-permeable. They protect lower lying layers from erosion, but once eroded, broken or fractured these lower layers erode rapidly. RUY ET AL. (1999) identifies the reason for the porosity and erodibility of soils as the weak soil matrix as well as structural and macro cracks. Also MARTINEZ-CASASNOVAS ET AL. (2004) verify the origin of sidewall erosion from variations in soil moisture content that influence shrinking and swelling of clay minerals and thus, the instability of the soils. Considering the high diurnal and seasonal rainfall variations and the semi-permeable character of the volcanic layers, soil moisture movement within the buried horizons can only take place horizontally. These dominantly unsaturated soil horizons are highly susceptible to erosion forces and consequently lead to the development of undercut hollows (MARTINEZ-CASASNOVAS ET AL., 2004). PALMER & RICE (1973) also highlight that over-consolidated clay in soils leads to increasing slip surface.

Since the erosion form 'barren degraded land' is known by farmers for more than 40 years (appendix 14.1, interview 2), and also one aerial photography from the 1940s displays these forms (however, to a smaller extent), it seems that these 'barren degraded lands' are more of structural than of anthropogenic origin. It is not known, whether the development of the 'barren degraded land' started after a natural threshold of erosivity forces was exceeded, or if anthropogenic influences started the development.

However, these forms were only observed in the watershed of the *Bilate River* and here, only in the *Rift Valley* and partially in the transition zone to the *Western Ethiopian Highlands*.

8.3 Soils and Soil Sediments

Special focus was given to the determination of the physical character and erodibility of the soils. Since data availability is very limited to the FAO data at scale 1:1,000,000, an attempt was carried out to obtain more detailed information about soils and soil sediments through sampling and analyses of soil horizons and layers of profiles. The locations of the individual profiles were selected where gullies, rims of 'barren degraded land' or trenches from road construction allowed access and sampling. Then, the profiles were spatial related to FAO soil units after exact location with GPS. The goal of analysing the samples was both the verification of the FAO ground data and the determination of soil parameters.

The results of the sample analyses show no distinct pattern of individual soil properties, both chemically and physically. Also, results from visual inspections in the field could not be verified through the results of a subsequent laboratory analysis. For example, in the *Rift Valley* several profiles show a white, strongly compacted layer beneath the topsoil where gullies and barren degraded land occur (fig. 88). The depth and vertical position of this layer in each profile is known from field research, but results from laboratory analyses do not confirm this layer.

Other determined soil characteristics such as pH-value, electric conductivity and magnetic susceptibility are all within a range typical for tropical soils (ZECH & HINTERMAIER-ERHARD, 2002), but its vertical pattern is uncommon. Only few profiles exhibit the vertical sequence of these characteristics that is known from the literature. Some observations are in stark contrast: samples from profiles located in the *Western Ethiopian Highlands* are associated with the FAO soil group Nitisol and were also identified as such in the field. Their magnetic susceptibility should be relatively high due to their high content of hematite, but this could not be verified in the laboratory.

Fig. 86: 'White Layer' investigated during Field Trips

High pH-values occur primarily in samples taken in the *Rift Valley*, but also in the *Western Ethiopian Highlands*, as well as in the *Valleys and Basin*. No correlation of pH-values to geology could be established. Only the electric conductivity shows an expected pattern: some profiles experience higher electrical conductivity beneath the topsoil, where weathering, as well as the formation of clay minerals, is higher. The grain size distribution is random across all profiles and particularly within the profiles.

Physical and chemical properties of soils are very strongly linked to the relief position (WANG ET AL., 2001), such as the position within the curvature or slope. They are also correlated to the small-scale relief position such as the location in areas of mountainous or flat character. The change of relief across the watershed on ground scale is quite dramatic. Thus, local influences dominate all soil properties. Next to these natural influences, the anthropogenic impact on soils and soil sediments in the watershed are severe. More or less the entire watershed is used for agriculture, pasture and agro-forestry. Intensive pasture is reducing the infiltration capacity due to trampling from livestock (SCHÜTT & THIEMANN, 2001). But also forests are used for pasture and thus, the same effect can be observed there.

Eucalyptus is the dominant plantation species that is also changing soil properties (LEMENIH ET AL., 2004). Cultivated fields show a distinct vertical profile: a ploughed topsoil layer is followed by a strong compacted layer in approximately 20 cm depth. This layer is semi-permeable (GEBREGZIABHER ET AL., 2005) where infiltration capacity is reduced, rooting depth is restricted, and weathering and formation processes are disturbed. Since agriculture has a long tradition in Ethiopia, this plough pan can be observed throughout the watershed where cultivation is taking place some 100 years (D'ANDREA ET AL., 1999).

The content of the organic carbon partially reflects the effect of this plough pan. Topsoils are of high and very high organic carbon content and a sudden transition towards much lower organic carbon content indicates layers that are only marginally influenced by organic carbon from the top. In general, the organic carbon content of the samples is not consistent with soil properties indicated from the FAO soil types.

However, all investigated properties of profile samples verify literature findings (ZECH & HINTERMAIER-ERHARD, 2002). But the overall random pattern in both the spatial and vertical dimensions does not allow any specific association of existing profiles to FAO soil units and therefore does only little facilitate the estimation of the spatial and vertical distribution of erodibility within the watershed.

One general trend was discovered during the analysis of the minerals and clay minerals: all samples show a relatively high content of amorphous clay minerals such as Allophane. Amorphous clay minerals are known to exist predominantly in volcanic sediments and basaltic bedrock. Both occur in the watershed. Since physical soil properties are of major importance for infiltration capacity and resistance to erosion and soil erosion and since physical soil properties are strongly linked to the content of clay minerals, Allophane are of major interest. They could be a weathering product but also the result of clay mineral formation which develops Allophane as a temporary product (WADA, 1989). Which kind of Allophane occurs in the watershed was not investigated, because it is not of interest in this study. But its occurrence shows that the soils in the entire watershed are vulnerable to erosion processes (ALLBROOK, 1985).

However, the attempt to associate the ground data to FAO data failed in this study. On one hand, the effect of downscaling from scale 1:1,000,000 to the ground must lead to uncertainties, such as wrong mapping and therefore wrong spatial overlay of the location of the profiles to the FAO data. On the other hand, the regional relief characteristics and the human impact on soil properties are more influencing the soil development than considered in the FAO ground data.

Since a proper investigation of enough soil parameters relevant for estimation of soil erodibility for the entire watershed is not feasible within this study, some FAO data were utilised as input parameters for estimating the erodibility of the soils (see chapter 9.1 and 9.2). It is known that these FAO data are of poor quality, but the aim of the model allowes only easy to investigate input data. Cost and time intensive analyses of several hundereds profiles are not of interest to run the model, although its scientific need is known.

8.4 Land Cover

The land cover differs very strongly within the watershed. Due to the dependence of the vegetation on altitude (HURNI, 1982), vegetation zones could be defined very clearly. But actual vegetation is not only dependent on altitude, but also on the availability of water, the degradation of the soil and the land use. In addition, inclination of the relief, as well as the impact of men and livestock movement influence the vegetation pattern (SCHÜTT & THIEMANN, 2001).

In general, an intra-annual cycle of vegetation cover was observed in the watershed that is strongly linked to human activities: within the study sites *Ana (WEH), Doyancho (WEH), Hage (WEH), Ofi (WEH), Sedebo (WEH-RV)* and *Agega (WEH-RV)*, similar distributions of the vegetation cover were surveyed. The immediate surrounding of the *tukuls* in general has quite high vegetation cover by grass, shrubs and trees. In greater distances to the *tukuls*, intensive land use leads to a different intra-annual vegetation cover. During the dry seasons, the vegetation cover is minimized as agricultural fields are used for livestock grazing. At the beginning of the rainy season, the vegetation cover on agricultural fields is zero and after some weeks vegetation cover is increasing and reaching its maximum at the harvest time at the beginning of the dry season. In the study site *Dimtu (RV)* the vegetation cover is sparse throughout the year. Pastoralism is the dominating land use in the *Rift Valley* and only few agricultural fields exist. However, the semi-arid climate minimizes the vegetation cover and most of the year shrubs and acacia trees are the only green vegetation.

The inter-annual changes of the vegetation cover are caused by climatic changes, such as the El-Niño effect and changes of the intensity of the Indian Monsoon (GREGOR, 2002). FULLER ET AL. (2003) postulate very clearly that the interpretation of land cover and land cover changes from satellite image classification needs extreme caution that is difficult to accomplish. Uncertainties of this methodology are known, especially the change of vegetation cover during alternating climatic seasons. Woody plants react differently than annual agricultural crops or grasses, since their roots can reach deep percolated water (WALKER & LANDRIDGE, 1996). Additionally, degradation of the vegetation due to overgrazing during the dry season is enhancing this effect. Whereas a direct correlation exists between grass vegetation and rainfall, this effect could not be observed with woody vegetation which is more subjected to be cut by men. Thus, annual vegetation dynamics are difficult to determine (KRAAIJ & MILTON, 2006).

The developed Land Cover Class Index (LCCI) gives general information about the distribution of the land cover within the watershed. It is one input parameter for the model (see chapter 9.1.1) and therefore its development was based on easy to derive parameters. However, the methodology for developing the LCCI shows some errors, but nevertheless the results are suffient for this model. A significant correlation between LCCI and NDVI data from the same month could not be determined, but a general trend of the spatial correlation was found. One one side the NDVI data themselves experience determination errors, for instance influence different top soil colours the spectral reflectance and thus the recording from satellite sensors (GREGOR, 2002). One the other side the LCCI is based on Landsat TM satellite images which also experience errors from processing. Additionally, the different grid cell sizes of both data sets prevent proper correlation results. More than 1000 cell information from the LCCI are spatially located in one NDVI cell and that must authomatically lead to levelling correlation results.

However, the result from the verification indicates general trends: LCCI classes of higher numbers are more located in NDVI cells of lower NDVI numbers and LCCI classes of lower order are more located in NDVI cells of higher numbers.