Impacts of land use changes on the hydrology of Wondo Genet catchment in Ethiopia



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Study track

Geohazards and Earth Observation

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1 Introduction

Water is the most essential requirement for all human activities such as drinking, agriculture and power generation. People would not survive without sufficient fresh water of good quality. Planet earth accommodates huge amounts of water, but only 1% is accessible as fresh water in lakes, rivers and aquifers (Jackson et al., 2001). The increasing human population over the last centuries has increased the pressure on this small fraction of accessible water. According to a report of the International Atomic Energy Agency (IAEA, 2011), two-thirds of the human population in 2025 will be confronted with water shortages and will not have access to save drinking water, even in regions where there is currently no water shortage.

Ethiopia is often referred as the water tower of East Africa, as it is one of the African countries that has an abundant water resource potential (Awulachew et al., 2007). However, much of the water resources are underutilized, as many people are suffering from water shortages. According to the NGO Water.org (http://water.org/country/ethiopia/) only 42% of the population has access to a safe fresh water supply and only 11% has access to adequate sanitation services. In the last 20 years, water shortage has increased as Ethiopia experienced several periods of drought, which caused food shortages and famines.

As in many parts of the world, the population in Ethiopia increased rapidly in the last century. This eventually resulted in large-scale land use changes, deforestation, overgrazing, expansion of crop land to marginal and steep sloping areas, poor soil management practices and unsustainable use of natural resources (Tesfahunegn et al., 2012). These practices reduce rainwater infiltration resulting in more surface runoff and water erosion. This leads to exhaustion of the soil, decreasing soil quality and eventually a decline in soil productivity (Bewket, 2003). Small scale farmers will be seriously affected by long-term consequences on land productivity. Ethiopia has 3.7 million hectare of potential irrigable land that can be used to improve agricultural productivity (Easton et al., 2010). However, the crop yields and livestock production in Ethiopia are still among the lowest in Africa (Sonneveld et al., 2011).

Understanding the hydrological processes is crucial towards better water and land resource management, as the hydrology largely influences soil erosion and is highly important to agricultural productivity (Easton et al., 2010). Widespread land use changes have often been associated with changes in the local hydrology as hydrologic responses of a catchment are influenced by land cover. Changes in land cover may lead to significant changes in evapo-transpiration, leaf area index, soil moisture content, infiltration rates, (sub-) surface flow regimes, surface roughness, surface runoff, and soil erosion through interactions with vegetation, topography, soils, geology and climate processes (Nejadhashemi et al., 2011).

Lake Awassa in the south of Ethiopia has experienced more and more problems with a rising water level of the lake over the last 30 years. Despite the basin being a closed system, which means that the water input is equal to the water output, the lake level has gradually risen. This caused multiple socio-economic problems such as the risk of floods in Awassa town, and decreasing fish stocks.

Previous studies related the rise of the lake level to large scale deforestation and climatic changes (Ayenew and Gebreegziabher, 2006; Olaka et al., 2010), but no conclusive evidence for those relations has been given yet.

Although the impact of land use change on hydrologic responses is widely studied, only a few studies were conducted in Ethiopia (e.g. Legesse et al., 2003; Bewket and Sterk, 2005). Legesse et al., (2003) modeled the impact of the change of arable land into forested land on river discharge, which showed a decrease in discharge, mainly caused by changes in evapo-transpiration rates. Bewket and Sterk (2005) studied the effect of expansion of agricultural land on flow regimes in the Chemoga river, which resulted in decreased dry season flow and no changes in peak flows. The Lake Awassa catchment being a closed catchment with only one perennial river and no outflow, there is a need to understand the correlation between land use change and hydrologic dynamics. However, no detailed studies on hydrologic responses of land use changes in the Awassa catchment exist yet. This study only focused on the Wondo Genet catchment, which is part of the Awassa catchment. Because of the large spatial differences in soil, land use and hydrological conditions within the Awassa catchment This research aimed to relate hydrologic responses to land use/cover changes for the past 40 years in the Wondo Genet catchment. The following objectives were defined for the study:

- To determine the main land use changes over the last 40 years in the Wondo Genet catchment.
- To determine the hydrological responses of the different land use types in the Wondo Genet catchment.
- To relate the hydrological changes to the land use changes over time in the Wondo Genet catchment.

2 Site description

This study was conducted at Wondo Genet catchment, which is geographically located at 6°45’ N to 7°15’ N latitude and 38°15’ E to 38°45 E longitude (Figure 1). The Wondo Genet catchment is part of the larger lake Awassa catchment. It is located at the eastern side of the Awassa lake and is bordered by the rift escarpment in the south and east and the main road between Addis Ababa and the Kenyan border in the north (Figure 1).

The Ethiopian Rift Valley is part of the Great East African Rift Valley; which is an active continental rift which divides the African plate into two new tectonic plates; the Somali Plate and the Nubian plate. These plates began to separate about 25 million years BP (Ayenew, 2007). The Great African Rift Valley extends from the Red Sea in the north to the Kenyan border in the south. The Ethiopian Rift Valley runs in southwest-northeast direction, and transects the uplifted Ethiopian highland. During the rift formation, extensive volcanism took place, and the rift is nowadays mostly covered with Cenozoic volcano and sedimentary rocks. The Ethiopian Rift Valley is still seismically active; the region has multiple geothermal features and caldera volcanoes (Ayenew, 2007).

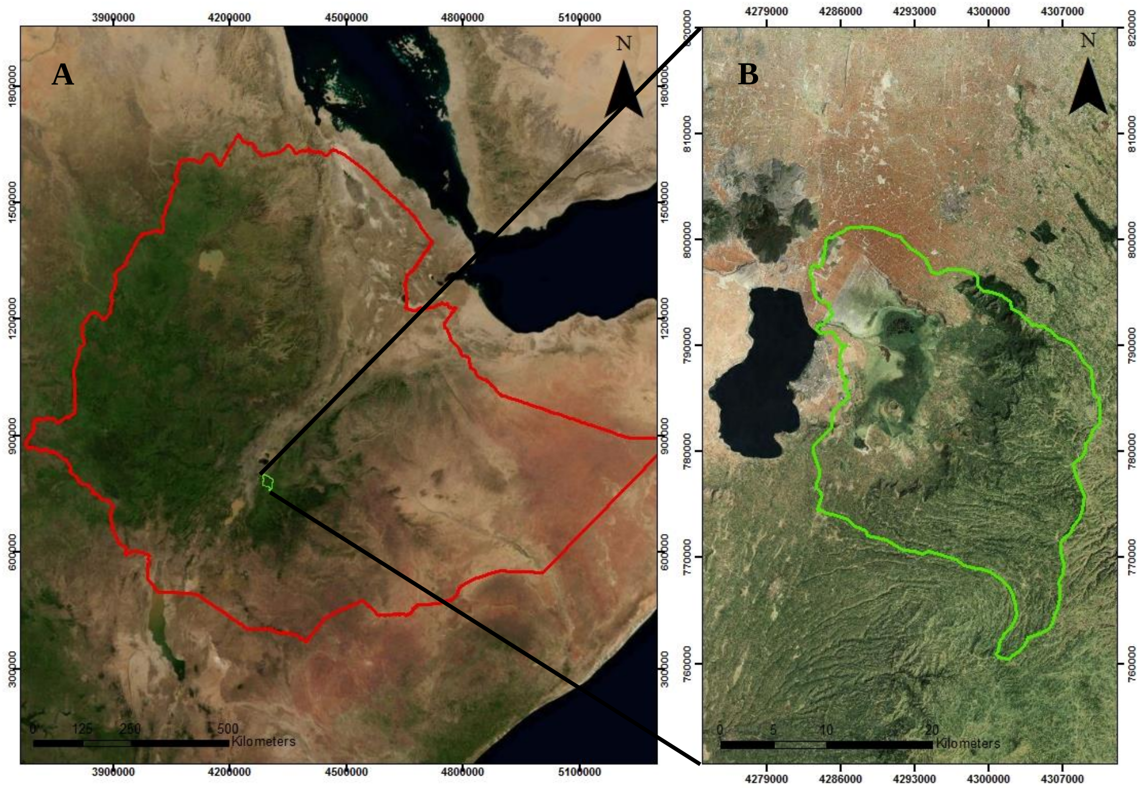

Figure 1: Map of Ethiopia (A) and the location of the Wondo Genet watershed in the Awassa catchment (B).

The Ethiopian Rift Valley contains many fresh and saline lakes; which were mainly formed in the depression of former tectonic activities. The Awassa catchment is one of the Rift Valley Lakes and is formed within two collapsed calderas of Pliocene age. The catchment is a closed system because it has no surface outlet. Lake Awassa receives surface water from the river Tikur Wuha, which in turn receives its water from the Shallo swamp in the eastern Wondo Genet catchment. Despite the catchment has no surface outlet, it is still a fresh water lake, because of its significant groundwater inflow (Olaka et al., 2010).

The Ethiopian Rift Valley has a moist sub-humid to semiarid climate, where evapotranspiration exceeds precipitation. The climate in the area is affected by the presence of the Inter-Tropical Convergence Zone (ITCZ) throughout the year. Therefore the region experiences mainly two seasons; a relative dry period from November to February with mean monthly minimum precipitation of 17.8 mm in December, and a relative wet period from March to October (Figure 2). Within the rainy season there are two rain periods; a short rain period between April and May and a heavier rain period between July and September. Awassa receives high precipitation rates; it varies annually between 600 and 1200 mm in the rain season (Masresha et al., 2011). The highest monthly rainfall is from June to September. The temperature varies from 12 °C in the rain season to 27 °C in the dry season (Abiye, 2007).

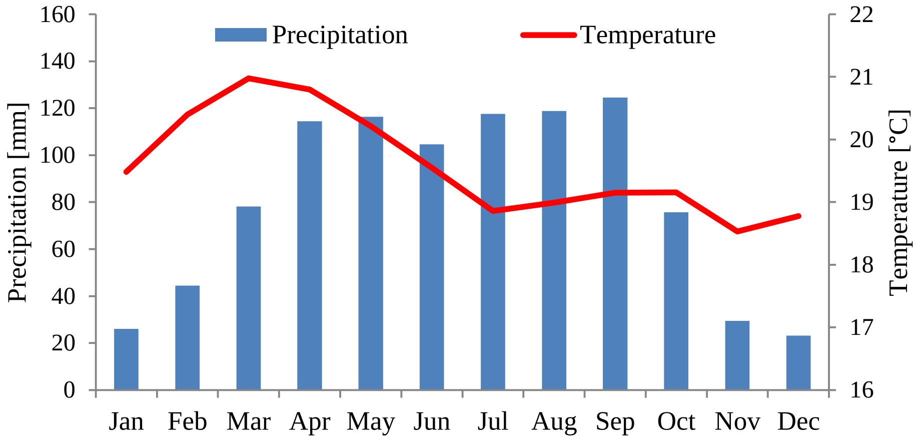

Figure 2: Average monthly precipitation and temperature for Awassa gage station (1978 - 2004), Ethiopia.

The Central Rift Valley is one of the most fertile areas in Ethiopia, but permanent settlement did not occur before the 1950s. Bandits, occurrence of Malaria and conflicts between tribes prevented people to settle in this area. But the rapidly growing population demanded more agricultural land and after the 1950's, more and more people began to settle in the area around the Awassa lake as infrastructure improved. The expansion of agricultural land use and lack of proper land management systems have reduced the naturally vegetated area. This resulted in an increasing pressure on the ecosystem since the 1950's (Legesse et al., 2003; G. Desse, personal communication, 2012).

The vegetation in the Wondo Genet area is influenced by altitude, rainfall and soil fertility. The Wondo Genet catchment can be divided into a lowland area and an upland area (Figure 3); the eastern side of the rift runs from northeast to southwest through the watershed. On the hill slopes of the rift escarpment, between 2000 and 3000 m, remnants of natural forests are found. The main tree species in those forests are *Podocarpus falcatus* and *Juniperus procera*. Deforestation is a serious problem in this area. The major causes of deforestation are population growth, agriculture, resettlement, grazing, fuel wood and timber exploitation (Tulu, 2011). 96% of the energy consumption in Ethiopia comes from fuel wood and charcoal, and illegal forest logging is a serious problem in this area.

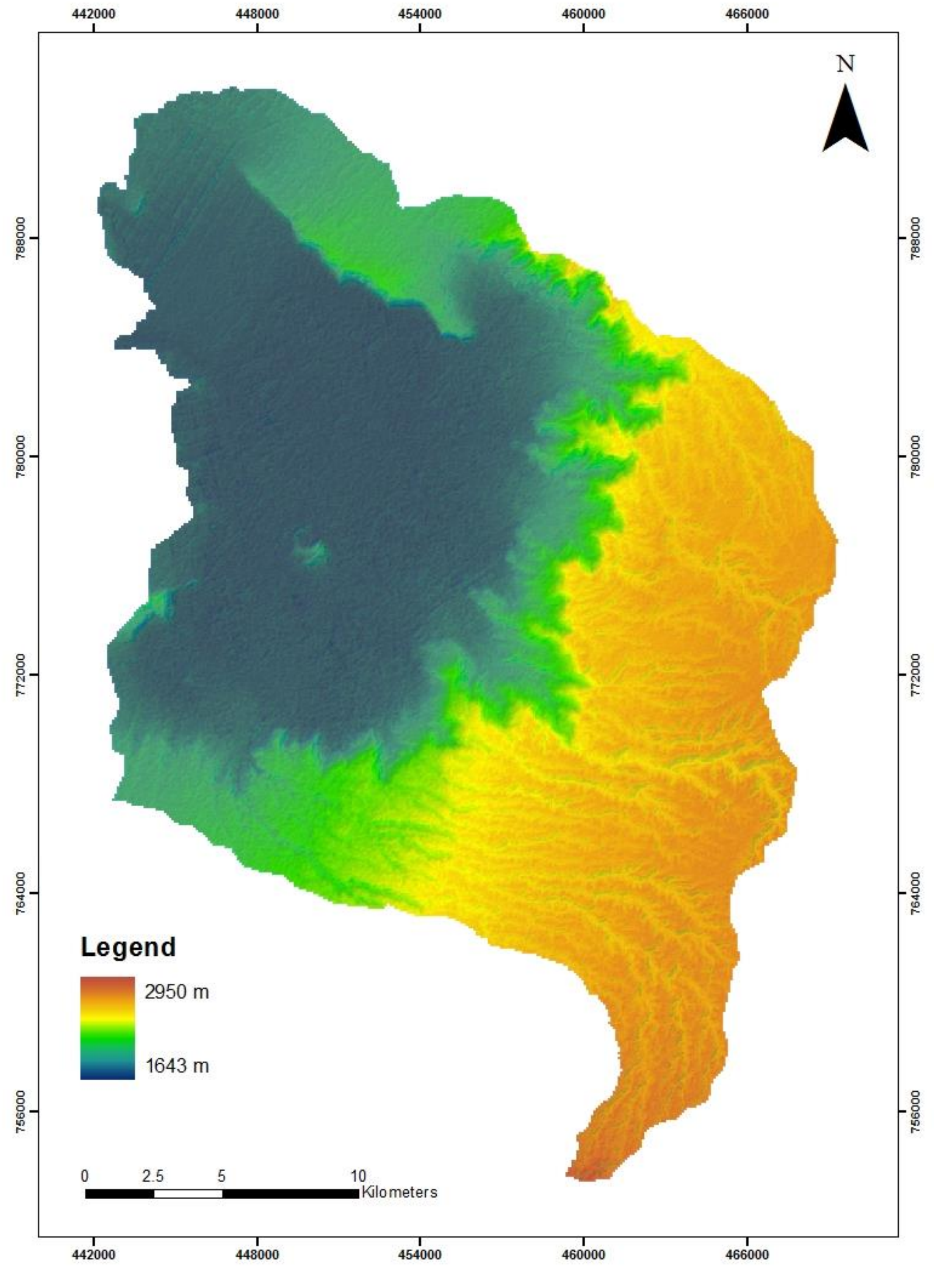

Figure 3: Digital elevation model (DEM) of the Wondo Genet catchment, Ethiopia.

On the lower slopes mainly grassland, bush land and acacia woodland prevail. Intense cultivation is found on large parts of the Rift Valley basin. The major crop production in the area includes ensete (or false banana) (*Ensete ventricosum*), sugarcane (*Saccharum officinarum*), maize (*Zea mays*) and potatoes (*Solanum tuberosum*). The cultivation of the cash crops coffee (*Coffea arabica*) and khat (*Chata edulis*) has increased rapidly during the last decades. Especially khat production has increased in this area, because of its high quality. In the Wondo Genet catchment area there is a clear distinction between smallholder fields and large agricultural farms. Smallholder farms (Figure 4) dominate the area and are usually small with an average lot size less than 2 hectares per household (Dessie and Kleman, 2006). The production of these farms is used for their own consumption and to make some money by selling agricultural products in the local markets. Crops are usually intercropped, such as khat with ensete and coffee with sugarcane (Figure 4B). The cropping system is permanent or semi-permanent and very little shifting in cultivation occurs (Getahun, 1978). Most smallholder farms own livestock (e.g. sheep, goat, cattle) and keep the animals on rangeland during the growing season. Large farms are usually owned by commercial companies and not so often by families. Their lot sizes are usually larger than 2 hectares and consist mainly of a monoculture cropping system. Main crops produced by those large enterprises are maize and sweet potatoes.

A **B**

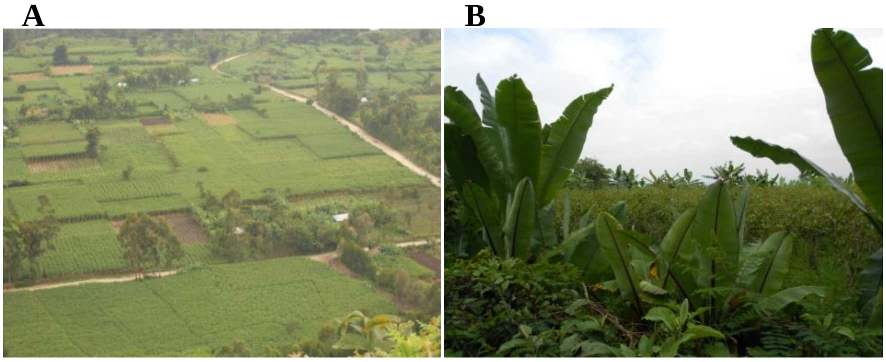

Figure 4: Smallholder farms (A) and intercropping agricultural system (B); khat surrounded by ensete.

The two main rainy seasons result in two main crop seasons; the Meher and the Belg. The Meher is the main crop season between September and February. Crops which are harvested between March and August are part of the Belg. Only smallholder farms have two crop seasons, large farms concentrate entirely on the Meher season as in this season crop yields are always better than in the Belg season (Dessie and Kleman, 2006).

3 Materials and methods

3.1 SWAT hydrological model

To investigate the impact of the recent land use changes on the hydrology of the Wondo Genet catchment, the Soil and Water Assessment Tool (SWAT) model was used. SWAT is a physically based catchment model which can predict the impact of land use change and management practices on water and sediment budgets in a catchment over a long period of time. SWAT has been tested in different tropical watersheds (Neitsch et al., 2011). The SWAT model is a catchment-scale hydrological model based on the principles of the water balance:

$$SW_t = SW_0 + \sum_{i=1}^{t}\left(R_{day} - Q_{surf} - E_a - \omega_{seep} - Q_{gw}\right) \qquad [1]$$

Where SW_t is the soil water content [mm], SW_0 is the initial soil water content on day 1 [mm], t is the time [days], R_{day} is the daily precipitation [mm], Q_{surf} is the amount of surface runoff [mm], E_a is the evapo-transpiration [mm], ω_{seep} is the amount of water entering the unsaturated zone [mm] and consists of the infiltration rate minus the capillary rise, and Q_{gw} is the amount of return flow [mm] (Figure 5). Figure 6 shows the basic SWAT processes after water is infiltrated into the soil. The model defines two phases; the land phase and the water, or routing, phase of the hydrological cycle. The land phase controls the amount of water and sediment movement, and the water phase is the movement of water in the catchment.

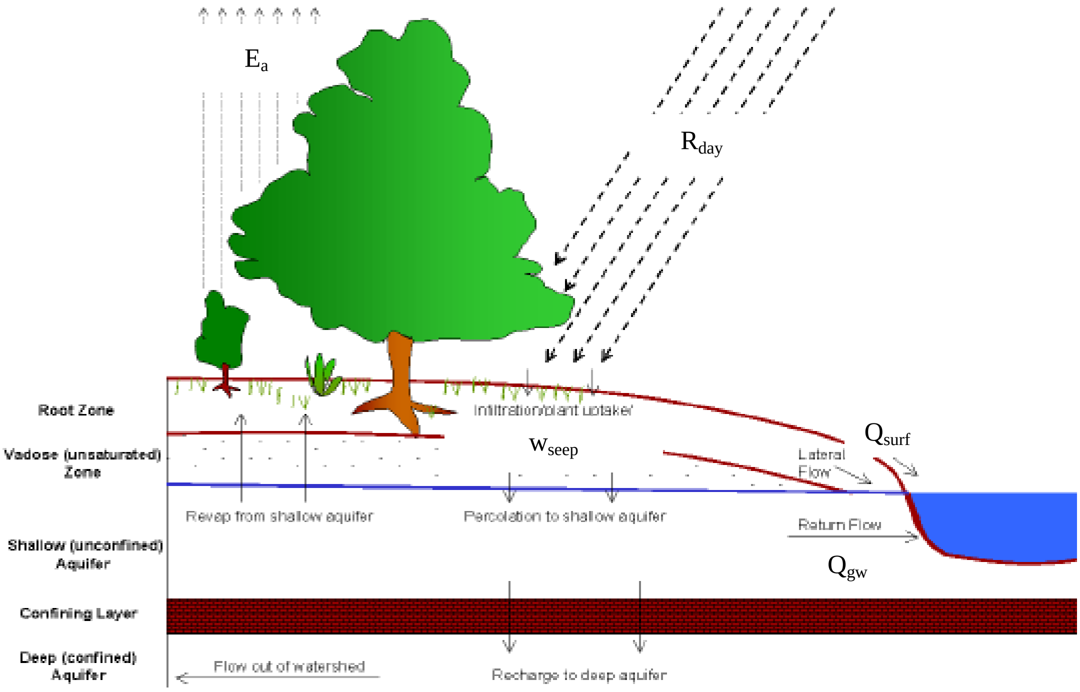

Figure 5: Schematic representation of the hydrological cycle (Neitsch et al., 2011).

The SWAT model divides the catchment in multiple sub-catchments depending on the number of tributaries within the catchment. The size of the sub-catchments varies from place to place and on the nature of topology and stream network system of the area. Each sub-catchment is divided into multiple hydrologic response units (HRUs), based on differences in soil, land use and slope. HRUs are lumped land areas with unique land cover, soil and management combinations. This can reflect differences in e.g. evapo-transpiration and runoff. The advantage of defining HRUs is that it increases the accuracy of the predicted loadings from catchment and gives a better description of the water balance for each individual HRU, as it has no interaction with other HRUs (Neitsch et al., 2011).

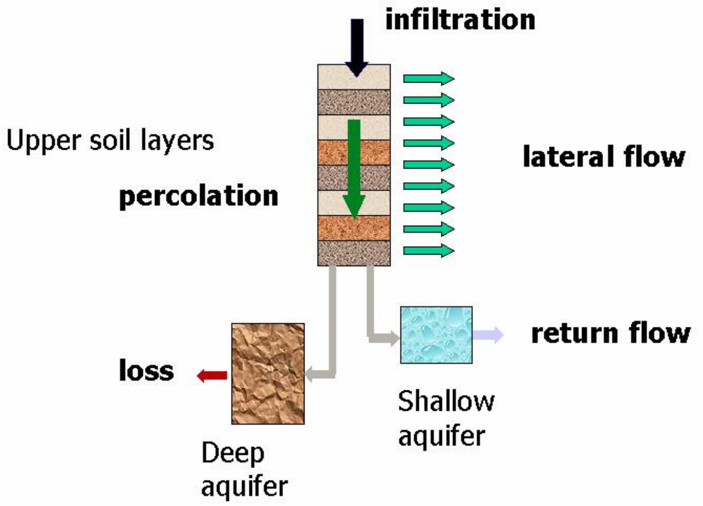

Figure 6: Schematic diagram of the sub-surface water fluxes (After Van Loon and Droogers, 2007).

The water balance for each HRU is represented by four storage volumes: snow, soil profile (0-2 m), shallow aquifer (2-20 m) and deep aquifer (>20 m) (David et al., 2007). Each HRU in a sub-catchment is liable for water and sediment movement, nutrients and pesticides loadings that are routed through channels, ponds and reservoirs towards the watershed outlet (Neitsch et al., 2011).

3.2 SWAT water balance components

3.2.1 Surface runoff

The SWAT model provides two approaches to estimate surface runoff; the SCS curve number method (USDA SCS, 1972) and the Green & Ampt infiltration (1911) method. In this study, the SCS curve number method was used, because this method estimates the surface runoff as a function of the soil's permeability, land use and antecedent soil water conditions. The method provides a consistent basis for estimating the amount of runoff under varying land use and soil types, and is easy to use when the land use is known. The SCS curve number method estimates surface runoff from daily rainfall using initial abstractions and a retention parameter. The SCS curve number equation is:

$$Q_{surf} = \frac{(R_{day} - 0.2\,S)^2}{(Rday + 0.8\,S)} \qquad [2]$$

Where Q_{surf} is the accumulated runoff [mm]. R_{day} is the rainfall depth for the day [mm] and S is the retention parameter [mm]. The initial value of the retention parameter S [mm] is defined as:

$$S = 0.9 * S_{max} \quad [3]$$

The maximum retention parameter S_{max} [mm] is defined as:

$$S_{max} = 25.4 * \left(\frac{100}{CN} - 10\right) \quad [4]$$

Where *CN* is the curve number for the day. The SCS curve number method is a function of the permeability of the soil, land use and antecedent soil water conditions. The SCS defines three antecedent soil moisture conditions (CN): I – dry (wilting poin), II – average moisture, and III – wet (field capacity). Typical curve numbers for moisture condition II are listed in multiple tables (e.g. Neitsch et al., 2011; Dingman, 1994). These values are appropriate for a 5% slope, to adjust the curve number to a different slope, the following equation is used (Williams, 1995):

$$CN_{2s} = \frac{CN_3 - CN_2}{3} * [1 - 2 * exp(-13.86 * slope)] + CN_2 \quad [5]$$

Where CN_{2s} is the moisture condition II curve number adjusted for slope, CN_3 is the moisture condition III curve number for the default 5% slope, CN_2 is the moisture condition II curve number for the default 5% slope, and *slope* is the average fraction slope of the sub-catchment. A more detailed description is given by Neitsch et al., 2011.

3.2.2 Evapo-transpiration

The SWAT model estimates values of the actual evapo-transpiration from soils and plants separately. Evapo-transpiration is the amount of evaporation from rivers, lakes and bare soil and the transpiration from vegetative surfaces. The actual evapo-transpiration is calculated by using the potential evapo-transpiration (PET); the PET is the volume of water that can be evaporated and transpired if enough water is available. The daily PET can be estimated by SWAT through three different methods: Penman-Monteith, Hargreaves or Priestley-Talor. The different methods all requires different amounts of inputs; data of relative humidity [-], solar radiation [MJ/m^2/day], wind speed [m/s] and air temperature [ºC]. In this study, the Priestley-Taylor (1972) method was used to calculate the daily PET, due to lack of the availability of daily meteorological data. This would have given unreliable PET values with the Penman-Monteith equation. The Priestley-Taylor equation is given by:

$$\lambda E_0 = \alpha_{pet} * \frac{\Delta}{\Delta + \gamma} * (H_{net} - G) \quad [6]$$

Where λ is the latent heat of vaporization [MJ/kg], E_0 is the potential evapo-transpiration [mm/d], α_{pet} is a coefficient, Δ is the slope of the saturation vapor pressure-temperature curve, *de/dT* [kPa/°C], γ is the psychrometric constant [kPa/°C], H_{net} is the net radiation [MJ/m^2/d] and *G* is the heat flux density to the ground [MJ/m^2/d] (Priestely and Taylor, 1972).

The actual evapo-transpiration is the sum of soil water evaporation and transpiration by vegetation. Soil water evaporation was estimated by using exponential functions of soil depth [mm] and water content [-]; a detailed description of these functions is given by Neitsch et al., 2011. Transpiration was simulated as a linear function of the PET and leaf area index (LAI [-]) and is given by:

$$E_t = \frac{E_0' * LAI}{3.0} \qquad 0 \leq LAI \leq 3.0 \qquad [7]$$

$$E_t = E_0' \qquad LAI > 3.0 \qquad [8]$$

Where E_t is the maximum transpiration on a given day [mm H_2O], E_0' is the potential evapo-transpiration calculated by the Priestley-Taylor equation [mm H_2O], and *LAI* is the leaf area index. The value for transpiration is the amount of transpiration that will occur on a given day when the plant is growing under ideal conditions. The actual amount of transpiration may be less than this due to a lack of water in the soil profile or nutrient deficits (Neitsch et al., 2011).

3.2.3 Soil-water interaction

The movement of water through the soil can be along various pathways; removal from the soil by evaporation or plant uptake, percolation, or lateral movement in the profile. The lateral movement through the soil is calculated by the kinematic storage model provided by Sloan et al. (1983). This model simulates two-dimensional subsurface flow. The SWAT model uses the storage routing methodology to calculate percolation for each soil layer in the profile.

3.2.4 Groundwater

The SWAT model incorporates shallow and deep aquifers. The shallow aquifer water balance consists of recharge entering the aquifer, groundwater flow, the amount of water moving into the soil zone in response to water deficits and the amount of water removed from the aquifer by pumping. The deep water aquifer water balance consists of percolation from the shallow aquifer into the deep aquifer and the amount of water removed from the deep aquifer by pumping. The SWAT uses different empirical and analytical techniques to account for all these components of the ground water distribution (Neitsch et al., 2011). Water routing in the SWAT model was done by using the Muskingum routing (Chow et al., 1998) method provided by SWAT, which is a variation of the kinematic wave equation.

3.2.5 Erosion

SWAT computes erosion caused by rainfall and runoff with the Modified Universal Soil Loss Equation (MUSLE) (Williams, 1975). The MUSLE predicts the average annual gross erosion as a function of the runoff factor. The MUSLE equation is given by:

$$sed = 11.8 * \left(Q_{surf} * q_{peak} * area_{hru}\right)^{0.56} * K_{USLE} * C_{USLE} * P_{USLE} * LS_{USLE} * CFRG \qquad [9]$$

Where *sed* is the sediment yield on a given day [metric tons], Q_{surf} is the surface runoff volume [mm H_2O/Ha], q_{peak} is the peak runoff rate [m^3/s], $area_{hru}$ is the area of the HRU [Ha], K_{USLE} is the USLE erodibility factor [0.013 metric ton m^2 hr/(m^3-metric ton cm)], C_{USLE} is the USLE cover and management factor, P_{USLE} is the USLE support practice factor, LS_{USLE} is the USLE topographic factor and $CFRG$ is the coarse fragment factor. A more detailed description of these factors are given by Neitsch et al. (2011).

3.3 Data collection

Data required for the modeling were collected from the Wondo Genet catchment. Meteorological data, land use/cover, river discharge, soil and land management data were collected from the study area in Ethiopia, during the months September, October and November of 2012. This period corresponded to the transition of the rainy season into the dry season, as September is the last month of the rainy season.

3.3.1 Climate and hydrology data

Meteorological data needed as input for the SWAT hydrological model was obtained from the National Meteorology Agency of Ethiopia. Climate inputs consist of daily precipitation [mm], mean, maximum and minimum temperature [ºC], relative humidity [-], wind speed [m/s] and solar radiation [MJ/m^2/day] (Neitsch et al., 2011). Meteorological data was available from four different stations in or nearby the Wondo Genet catchment, from 1978 to 2007 (appendix 2). Daily discharge measurements of river Tikur Wuha were obtained from Hawassa University of Agriculture for the period 1980 – 2003. River Tikur Wuha is the outlet stream of the Wondo Genet catchment, these measurements were used to calibrate and validate the SWAT model.

3.3.2 Land cover

To evaluate land use changes, initially Landsat satellite images were used with a Universal Transverse Mercator (UTM) projection and a 30m resolution. Images from December 1986, December 1994 and January 2011 have been obtained from the internet, and were used to create land cover maps. In the fieldwork period, ground truth locations of different land covers were created for a supervised classification of the Landsat 2011 image. These exact locations were needed to have accurate reflection responses of each land use type. A supervised classification creates a classified map of training sites (ground truth locations) defined by the producer.

3.3.3 Soil data

Soil data was needed as an input for the SWAT model. A detailed soil map of the Wondo Genet catchment was obtained from the Hawassa University of Agriculture. The dominant soil types in this area are Cambisol and Luvisols. In compare with the highland area of Ethiopia, these soils are relatively young and inherently more fertile (FAO, 1993).

3.3.4 Management

Another input of the land phase of the hydrological cycle is the management factor. The important management practices were defined for each different land use type. This includes the beginning and the ending of the growing season, irrigation applications, use of pesticides and fertilizers and the tillage operations. The data needed for this information was collected from previous studies, field observations and informal interviews with the local farmers.

3.3.5 Routing

To route water and sediment through the catchment, a digital elevation model (DEM) was needed. An ASTER global DEM was available for the study area, which has a resolution of 30m (Figure 4). The DEM was used to calculate the area of the catchment and sub-catchment boundaries, as well as slope values.

3.4 Data analysis and model application

3.4.1 Data analysis

After the fieldwork, an analysis of all the collected data was made. The Landsat satellite images (30 m resolution) were classified using a supervised maximum likelihood classification provided by Erdas Imagine software and the ground truth polygons collected in the field. The land cover in the study area was divided into 7 classes; smallholder agricultural fields (<2 hectares), large agricultural farms (>2 hectares), natural forest, rangeland, open bush land, wetland and water body, which are the main land cover types in the area. To validate the correctness of the supervised maximum likelihood classification, the output of the Landsat satellite image of 2011 was compared with the ground truth data collected in the field, to establish correct classification of the land cover types. The spectral signature of the correct land cover types were used for a supervised classification of the Landsat satellite images of 1986 and 1994.

The meteorological data was evaluated to detect any significant meteorological trends in the period 1986 – 2011. Moreover it was evaluated if there have been years in the same period with extreme amounts of precipitation or temperatures.

3.4.2 Model application

The SWAT model was used for modeling hydrologic responses in relation to land use changes in the Wondo Genet catchment. By using the DEM, the SWAT model calculated the catchment area, stream network and the sub-catchments. The creation of the sub-catchments was important, as it created the boundaries for the further simulation. The model created an upper and lower threshold value for the size of the sub-catchments; the actual threshold value was defined by the user. By using the DEM, soil and land cover map, the SWAT model established 357 different HRUs, based on unique combinations of these maps. After that, input parameters of land cover and soil were adjusted according to field observations and management operations such as irrigation and application of fertilizers were added. To incorporate the land use change in the SWAT model, SWAT created land use update files with description of the changing land use types, location of the sub-catchment and the percentage of area which changed.

3.4.3 Sensitivity analysis

There are multiple parameters which affect complex hydrological modeling; most of them are not exactly known due to spatial variability, measurement errors, incompleteness in description of processes, etc. Therefore, optimalization of internal parameters of the SWAT model is an important task in order to achieve the best representative hydrological model. This is done by model calibration. Before calibrating a model, the most sensitive model parameters must be known. A sensitivity analysis determines the sensitivity of the input parameters by comparing the output variance due to the input variability. The sensitivity analysis was carried out to identify the sensitive parameters of the SWAT model. It was performed on 26 different parameters. Observed stream flow data of the Tikur Wuha River from 1/1/1980 to 31/12/2003 was used. By applying default upper and lower boundary parameter values, the parameters were tested for sensitivity for the simulation of the stream flow. After the analysis, the parameters were ranked according to their magnitude of response. Out of the 26 parameters, the 7 most sensitive parameters were chosen for model calibration (Table 1).

Table 1: Ranking of the 7 most sensitive parameters and their variation range for auto calibration.

Parameter	Description	Range
ALPHA_BF	Base flow recession constant	0-0.3
GWQMN	Threshold water depth in the shallow aquifer for base flow [mm H_2O]	0-5000 mm
CN2	Initial SCS CN II value	-15% to 15%
ESCO	Soil evaporation compensation factor	0-1
REVAPMN	Threshold water level in shallow aquifer for revap [mm H_2O]	0-1000 mm
SOL_AWC	Available soil water capacity	-15%-15%
SURLAG	Surface runoff lag coefficient	0-10

3.4.4 Model calibration and validation

Model calibration was done to improve the results of the model simulation, to adjust for uncertainties. The calibration was supported by the sensitivity analysis, which avoids performing calibration on non-effective parameters. The 7 most sensitive parameters were used to calibrate the model (Table 1). Like most other models, SWAT compares simulated data with the observed data to calibrate the model through parameter evaluation. The calibration is typically done by comparing stream flow data. In this study, discharge data of the river Tikur Wuha from 1990 to 1994 was used for model calibration. SWAT recommends calibrating first the water balance and then the temporal flow (Neitsch et al., 2011). Water balance calibration takes care of the overall volume and its distribution within the catchment, whereas the temporal flow calibrates for the flow time lag and the shape of the hydrograph.

The validation of the model was carried out using the calibrated parameters. The observed stream flow data of the river Tikur Wuha from 1995 to 1999 was used to validate the model.

3.4.5 Model performance assessment

The predictive capacity of the SWAT model for discharge was determined by using two statistics: the E_{ns} and the RMSE . Discharge measurements of river Tikur Wuha were used as observed input data. The Nash-Suttcliffe simulation efficiency (E_{ns}, Nash and Sutcliffe, 1970) indicates the goodness of the 1:1 fit between the observed and simulation discharge data. Values of ENS range from -∞ to +1, where 1 indicates a perfect match between the observed and simulated data. The expression of the Nash-Suttcliffe simulation efficiency is:

$$E_{ns} = 1 - \frac{\sum_{i=1}^{n}(Y_{oi} - Y_{si})^2}{\sum_{i=1}^{n}(Y_{oi} - \hat{Y}_{oi})^2} \qquad [10]$$

Where Y_{oi} the observed stream flow on day i, Y_{si} the simulated stream flow on day i and $\hat{Y}_{oi}$ the average measured stream flow value during the simulation period. The simulation is considered well if ENS>0.75 and satisfying if 0.36<ENS<0.75 (Van Liew and Garbrecht, 2003).

The root mean square error (RMSE) indicates the error between the observed and the simulated stream flow data. Values of RMSE close to zero indicate a good model performance (Alansi et al., 2009):

$$RMSE = \sqrt{\frac{\sum(Y_{si} - Y_{oi})^2}{n}} \qquad [11]$$

Where Y_{si} is the simulated stream flow and Y_{oi} is the observed stream flow on day i, and n the total number of outputs.

4 Results and discussion

4.1 Land use changes in the Wondo Genet catchment

Major land use changes in the Wondo Genet catchment occurred in the period between 1986 and 2011. In the Wondo Genet catchment, there are natural vegetated areas, which are open bush land, natural forest, rangeland and wetland, small and large agricultural fields and water bodies. Open bush land mainly covered by grassland, bushes and some trees. Natural forest consists of mixed type, dense forest in this area. Rangeland is mainly grassland which is used for grazing. Small agricultural fields (< 2 Ha) are smallholder farms with usually intercropping systems and with crops which are cultivated multiple years, whereas large agricultural fields are mainly dominated by commercial agriculture with monoculture cropping systems. The wetland cover is the swamp area, which is a fluctuation between grass and water cover.

Table 2 presents the statistical summaries of the different land use. Figure 7 shows the major land use types in the catchment for the different years. A more detailed description of the land use changes is given in appendix 3.

Table 2: Land use change in the Wondo Genet catchment, Ethiopia, between 1986 and 2011.

Land cover type	Area in 1986		Area in 1994		Area in 2011		Change	
							1986-1994	1994-2011
	Ha	%	Ha	%	Ha	%	%	%
Natural forest	7758	13.6	7302	12.8	2860	5.0	- 0.8	- 7.8
Rangeland	8367	14.7	3274	5.7	4618	8.1	- 9.0	+ 2.4
Open bushland	16250	28.5	19584	34.4	20750	36.4	+ 5.9	+ 2.0
Large size farmland	4685	8.2	7507	13.2	10976	19.3	+ 5.0	+ 6.1
Small size farmland	14721	25.8	15801	27.7	11582	20.3	+ 1.9	- 7.4
Wetland	4673	8.2	3102	5.4	6176	10.8	- 2.8	+ 5.4
Water body	509	0.9	392	0.7	-	-	- 0.2	- 0.7

As in most parts of Ethiopia, dramatic forest decline occurred over the last decades. Forest cover in the Wondo Genet catchment reduced from 13.6% in 1986 to 5.0% in 2011 (Table 2). The same forest decline pattern was reported by Dessie and Kleman (2003); they reported a relative forest decline from 16% to 2.8% in the Wondo Genet catchment in the period 1972-2000. The minor difference between these studies is the area of the study catchment; Dessie and Kleman (2003) studied only the area which was covered with forest. Currently the forest cover is mainly found on the escarpments of the rift valley, while back in 1986 there was still some forest cover left in the upland zone.

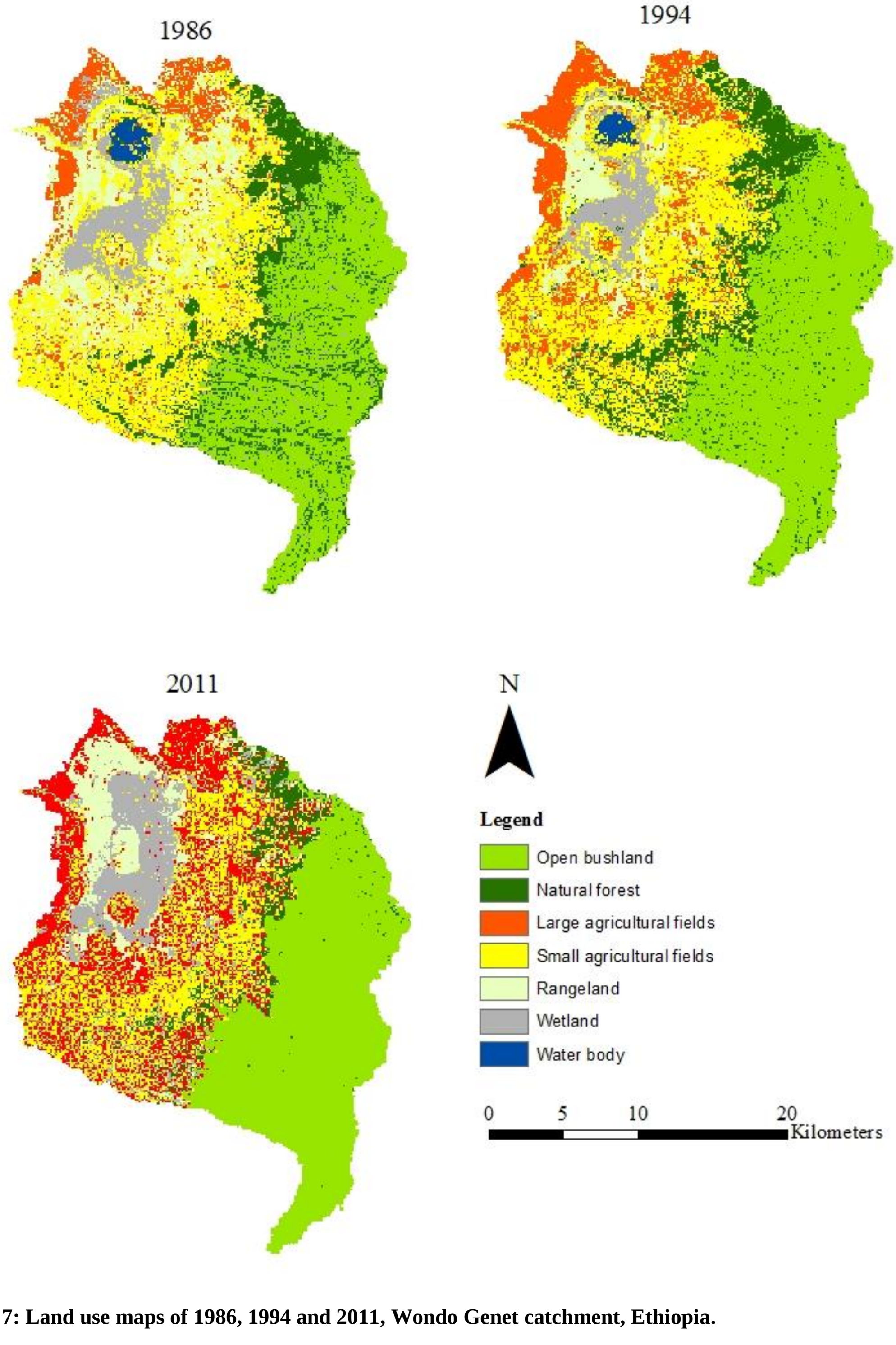

Figure 7: Land use maps of 1986, 1994 and 2011, Wondo Genet catchment, Ethiopia.

In the Wondo Genet catchment, the main reason for reduction in forest cover is the conversion of forest into open bush land and agricultural land. The conversion from forest into open bush land was mainly due to settlements and (illegal) logging for charcoal production (Figure 8B). Mid-1930s, three sawmills were opened for commercial logging in the area around Wondo Genet. The cleared area was immediately converted to small settlements and farmland. One sawmill in Wondo Genet was closed in the early-1970s; the other two remained operational until the mid-1980s. However, there is still a lot of illegal logging in the area (Figure 8). As 90% of the energy in Ethiopia comes from charcoal, many people still rely on illegal logging and charcoal production as their main source of energy (Dessie and Kleman, 2007).

As shown in Figure 7, most of the farmland in the Wondo Genet watershed is found on the fertile lowland. The area of farmland expanded rapidly; total farmland increased from 19406 Ha in 1986 to 22558 Ha in 2011 (Table 2). This category includes smallholder fields (average field size < 2 Ha) and large agricultural farms. Differentiating between crops was not possible for land use classification due to the restricted resolution of the available Landsat images (30 m). Most of the smallholder fields are smaller than the Landsat resolution of 30 m and this will result in too much error between the classified pixels.

Figure 8: Making of charcoal (A) and (illigal) logging (B).

Smallholder farms expanded by 1.9% between 1986 and 1994, but decreased by 7.4% between 1994 and 2011. Large agricultural fields expanded by 11.1% within the watershed between 1986 and 2011. As shown in Figure 7, especially between 1994 and 2011 many of the smallholder farms turned into large agricultural fields. Large agricultural fields are mainly cultivated with maize and potatoes in this area. The large fields are found mostly in the northern part of the catchment (Figure 7), where the soil is shallow and flat, and the area can be easily irrigated with water from the swamp area.

Smallholder farms are still dominating the agricultural land use. Almost every household in this area has their own small piece of land where they can cultivate different types of crops. In the Wondo Genet area most households cultivate crops such as ensete (false banana), sugarcane, maize, potato and the cash crop coffee. With the immigration of more people to this area, fertile land became scarce and people had to settle on the escarpments of the rift valley where the land was cleared. Due to its steepness and the restrictions of water holding capacity of the soil, this area is less suitable for cultivating crops such as corn and potato. With the introduction of the new cash crop khat more people began to cultivate this crop for its economic benefits.

The area occupied by rangeland fluctuated between 1986 and 2011. In 1986 rangeland was distributed throughout the lowland area, but in 2011 rangeland is mainly found at the northwest side of the swamp area. Reasons for this shift can be that around 1986 more land was used for grazing. However, as human settlement expanded, land became scarce and for food security reasons, most of the remaining grazing land was turned into crop land. The rangeland area around the swamp is subject to fluctuations in water availability; in dry periods some parts of the swamp turn into grassland, while in wet period's grassland become part of the swamp again.

The area of wetland fluctuated between 1986 and 2011, as shown in Figure 7. Fluctuations of wet and dry periods cause an alternation in swamp, water or grassland cover. Therefore land use classification in this area depends on the date of capturing the Landsat image. All images were captured in the dry season in December and January. Fluctuations in rates of precipitation during previous months can cause differences in water availability throughout the years and can cause variations in size of grassland, swamp and water body. In the past decades, the catchment experienced a negative feedback between the demand of water and the expansion of agricultural fields. As a result of the expansion of agricultural fields, more water is pumped from the lake for irrigation in the upstream area of the wetland, which results in drying up of the wetland and can be used for the expansion of agricultural fields. The main crop cultivated on these fields is maize. The root system of maize is shallow so the upper soil layer must contain sufficient soil moisture to take up the required water. Another advantage of growing maize is the growing time of 6 months, which covers the dry period and is harvested before the area become again too swampy.

The water body, which previously was called Lake Cheleleka, decreased from 0.9% in 1984 to 0% in 2011. During the field trip in September 2012, there were still a couple of small water bodies remaining, but they were too small to be distinguished on the Landsat image. It is not known if any of these water bodies were also there in January 2011, because January is in the middle of the dry period, whereas September is the end of the wet period. It is possible that the water bodies dried up in January 2011, and filled again in September 2012. Geothermal inflow in the swamp area provides a continuous inflow of warm water, which still results in a small permanent warm water body. Previously this warm water inflow was at the bottom of the lake, while currently it forms a separate small warm water body among other small cold water bodies. Much of this warm water is drained towards the surrounding villages. Local sources reported that almost the whole swamp area was a lake about 50 years ago. They stated that much of the feeding streams dried up or that the discharge of the streams substantially declined.

According to Figure 7, open bush land dominates in the upland area of the watershed. No ground truth data was available because this area was too remote. Classification in this area is based on people's accounts and spectral similarities of ground truth data from elsewhere in the watershed. The upland area is occupied by bush and grassland with spare areas of forest cover and small settlement. The area is mainly used for grazing land. Figure 6 shows that the forest cover declined over time; 50 years ago the area was dominated by natural forest cover, but with the introduction of sawmills in the area the forest cover almost disappeared.

4.1.2 Land use changes in Wondo Genet catchment in relation to other parts of Ethiopia.

Trends in land use change in the Wondo Genet catchment are similar to many other parts of Ethiopia. Growing pressure from human population caused extensive deforestation all over Ethiopia. Wood for fuel and expansion of agricultural land and settlement are the main reasons for forest decline (Teka et al., 2013). Most studies related to land use change are reporting extensive forest decline until the 1990s. However, some studies reported a positive development of the forest preservation in the last decade, but the forest protection is still not a necessity among local communities (e.g. Zeleke and Hurni, 2001; Alemayehu et al., 2009; Teka et al., 2013). Most of these studies were conducted in the northern part of Ethiopia, where settlement occurred overall much earlier than in the Central Rift Valley.

Only a few studies of land use changes were conducted in the Rift Valley of Ethiopia. However, all of these studies also reported the constant rate of conversion from rangeland and natural forest into arable land use (Dessie and Kleman, 2007; Garedew et al., 2009; Tsegaye et al., 2010; Biazin and Sterk, 2013). Biazin and Sterk (2009) reported that most of the farmers in the Central Rift Valley are still increasing their fields by clearing forests and grasslands, but at a slower rate than in previous decades. Dessie and Christiansson (2011) reported that forest decline in the Awassa catchment can be linked to social, economic and political patterns. Agricultural government policies have always played an important role in the agricultural systems in Ethiopia. This resulted in significant changes in land use patterns all over Ethiopia. Between 1974 and 1991 Ethiopia had a communist regime which imposed the first uniform land tenure system for Ethiopia. In 1985, the government came up with a new settlement policy; villagization. People were forced to live in communities, which resulted in compact settlements and outlying fields became abandoned. This implicated an increase in large agricultural fields around these communities. Since 1991, the current regime has implemented improved policies on the use of non-agricultural land, as well as the abolition of the villagization policy. These changed policies have resulted in an increase in bush land and protection of remaining forest, whereas the abolition of villagization resulted in an increase of smallholder settlement (Teka et al., 2013). Policies for the protection of the remaining forest are still not controlled by the government and the interest of preservation of the remaining forest is lacking. This is clearly seen in the Wondo Genet catchment in terms of illegal logging. The trend of the agricultural changes forced by governmental policies is seen in many parts of Ethiopia (Teka et al., 2013), but it is not clear in the land use change in this study; this would have resulted in an increase in large agricultural fields between 1986 and 1994, and a decrease between 1994 and 2011. Also the decrease of smallholder farms between 1994 and 2011 cannot be explained by this policy shift. However, settlement in this area did not begin until the early 1950s and for a long period of time the Wondo Genet catchment was hardly accessible by road (Desie and Christiansson, 2011), so settlement occurred not as early as in other parts of Ethiopia and was not much influenced by governmental policies.

4.2 Implications for the hydrological balance in the catchment

4.2.1 Stream flow calibration and validation

The SWAT model calibration and validation was done using the observed stream data of river Tikur Wuha between 1980 and 2003. This is the only stream flow gage station in the Wondo Genet catchment, therefore the SWAT model was only calibrated and validated with the stream flow data of this gage station. The calibration period was chosen between 1991 and 1994, whereas the period between 1995 and 1998 was chosen for validation of the SWAT model. The input parameters for calibration were based on the output parameter values of the sensitivity analysis, which are given in table 3.

Table 3: Input parameters values for calibration.

Parameter	Range	Best value
ALPHA_BF	0-0.3 [-]	0.011
GWQMN	0-5000 [mm]	85.79
CN2	-15% to 15%	CN2 * 1.13
ESCO	0-1 [-]	0.743
REVAPMN	0-1000 [mm]	324.0
SOL_AWC	-15%-15%	0.001
SURLAG	0-10 [days]	0

Figure 9 shows the final measured and modeled stream flow [m^3/s] between 1981 and 2007, table 4 shows the additional statistics of the calibrated and validated period between the measured and modeled stream flow data. The modeled stream flow data shows less fluctuations than the measured stream flow data. The ENS and RMSE values of both the calibrated and validated period are not very satisfying; due to a lack of data availability, the SWAT model was calibrated with only one measured stream flow data set with multiple gaps, as shown in figure 9; it would more accurate to calibrate with multiple measured data sets. The differences between the modeled and measured stream flow data can be the difficulties in implementing the swamp action into the model. The swamp acts as a reservoir in the Wondo Genet catchment, but it is hard to adjust the SWAT model correctly for the reservoir effects. The area of the reservoir is based on the average area of the classified wetland.

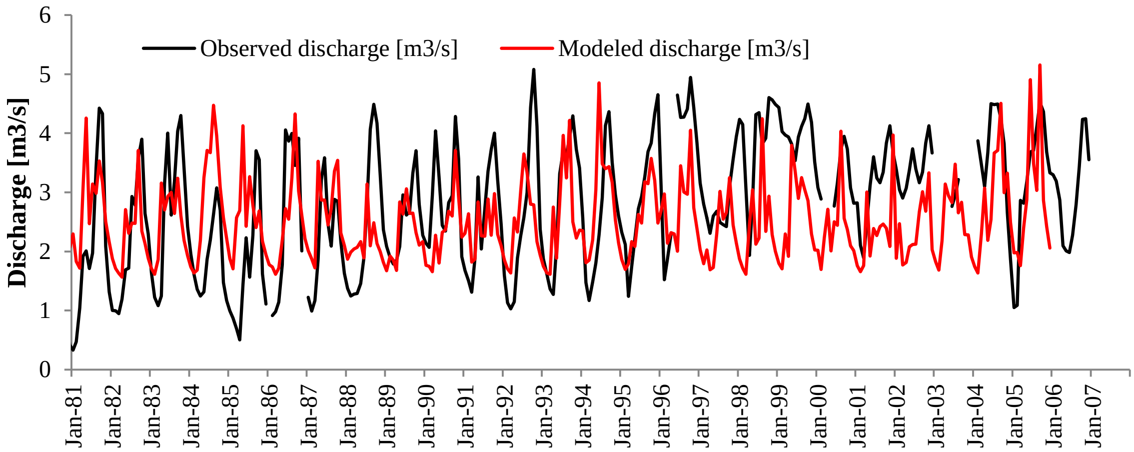

Figure 9: Modeled and measured stream flow [m^3/s] between 1981 and 2007, river Tikur Wuha.

Table 4: Statistics for the calibration and validation period between the measured and modeled stream flow data.

Application	Period	ENS	RMSE
Calibration	Jan 1990 – Dec 1993	0.12	6.3
Validation	Jan 1994 – Dec 1997	0.15	6.8

4.2.2 Hydrology in the Wondo Genet catchment

Measured data of the stream flow in river Tikur Wuha shows a significant increase in discharge (Figure 10). Although there is missing data between 2000 and 2004, the overall trend of measured data shows a significant increase in discharge. This trend has to be the result of changes in hydrology in the upstream area, as there is no evidence that the increase in discharge is the result of changing behavior of the river itself.

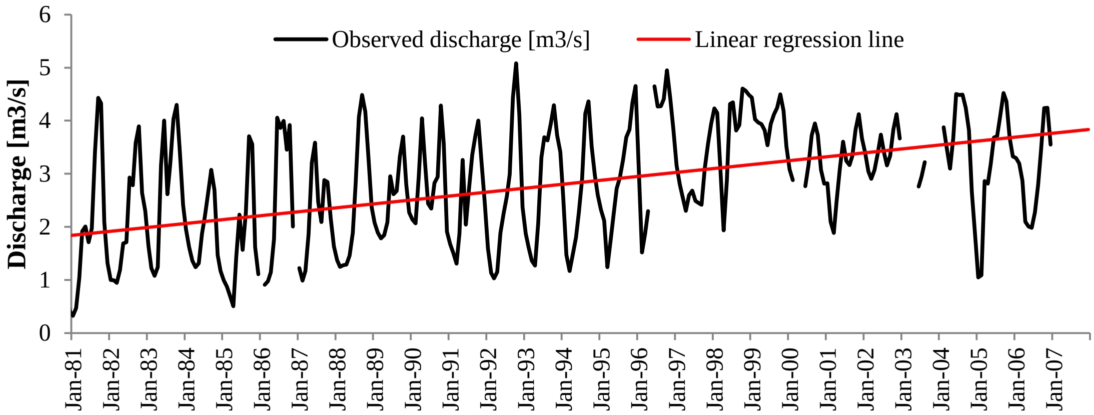

Figure 10: The trend of stream flow [m3/s] of river Tikur Wuha, between 1981 and 2007.

One of the input variables was daily precipitation. Daily precipitation data were available for four different rain gage stations in and nearby the Wondo Genet catchment. Exact locations of these gage stations are found in Appendix 2. The monthly precipitation graph (Figure 11) does not show any significant changes in rates and intensity. The location of this gage station is in the upstream area of river Tikur Wuha, so it is not likely that the increase in discharge is the result of increased precipitation.

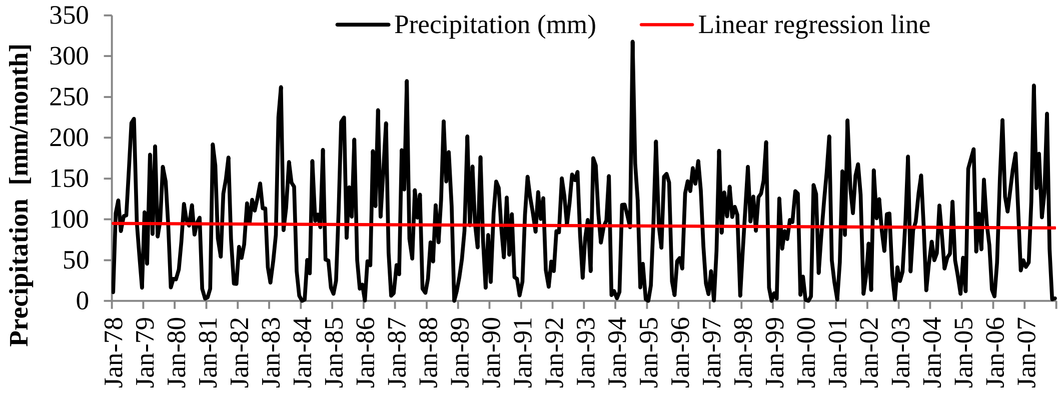

Figure 11: Precipitation [mm/month] for the Wondo Genet gage station.

The precipitation spatially varied within the catchment; therefore it was more accurate to have multiple rain gage stations. The graph in Figure 12 shows that there is slightly more precipitation around Wondo Genet and Hassawita, than around Awassa and Shashamene. The gage stations at Wondo Genet and Hassawita are situated near the rift escarpment, while the gage station at Awassa is in the lowland, and the Shashamene station is on the upland. Figure 12 shows the mean precipitation distribution around the year for the different gage stations. The area has two rain seasons; one between March and May and one between July and September. The dry season begins in October and ends in

March. This pattern is almost the same between the gage stations, despite they are situated at different elevations and locations.

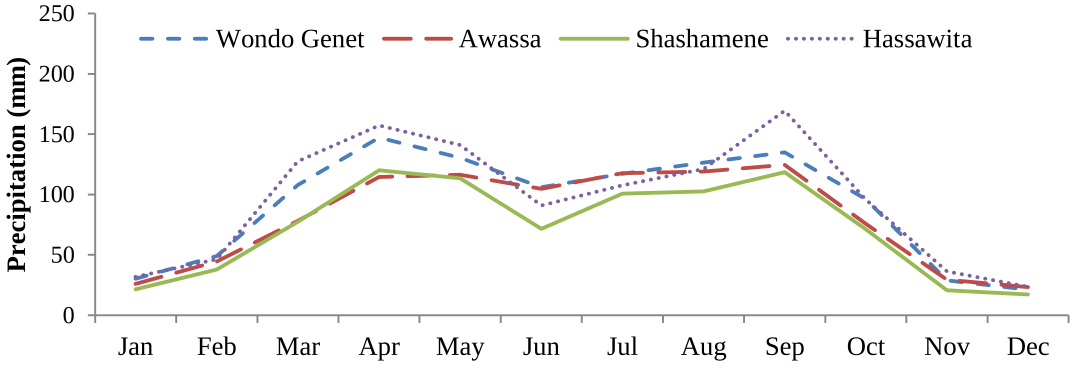

Figure 12: Mean monthly precipitation for the gage stations around Wondo Genet catchment, Ethiopia, between 1978 and 2007.

One of the components of the hydrological cycle in the catchment is the evapo-transpiration factor. Figure 13 shows the actual evapo-transpiration [mm] over the whole Wondo Genet catchment for each month between 1978 and 2007. This is the mean soil water evaporation and transpiration by plants [mm/month] combined over the whole catchment. The linear regression line shows a decreasing trend in the monthly actual evapo-transpiration. A decline in evapo-transpiration can be result of less precipitation, increasing temperatures and/or land use change. As figure 11 shows, precipitation did not change in this period, it is likely that land use change had an impact on the actual evapo-transpiration rate.

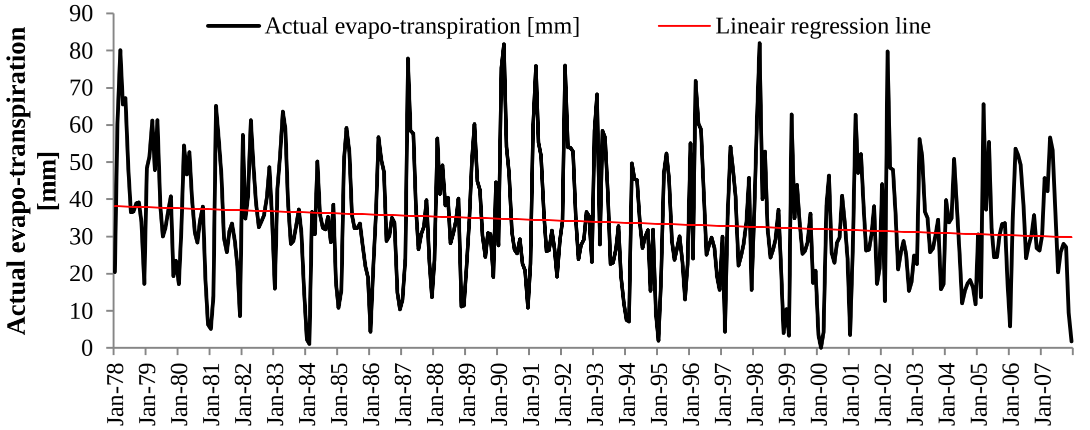

Figure 13: Mean monthly actual evapo-transpiration, Wondo Genet catchment, Ethiopia

Increasing rates of surface runoff can also be an explanation for the increasing discharge. However, Figure 14 shows no significant changes in surface runoff in the Wondo Genet catchment over time and most likely it does not significant contribute to the increase in discharge of river Tikur Wuha.

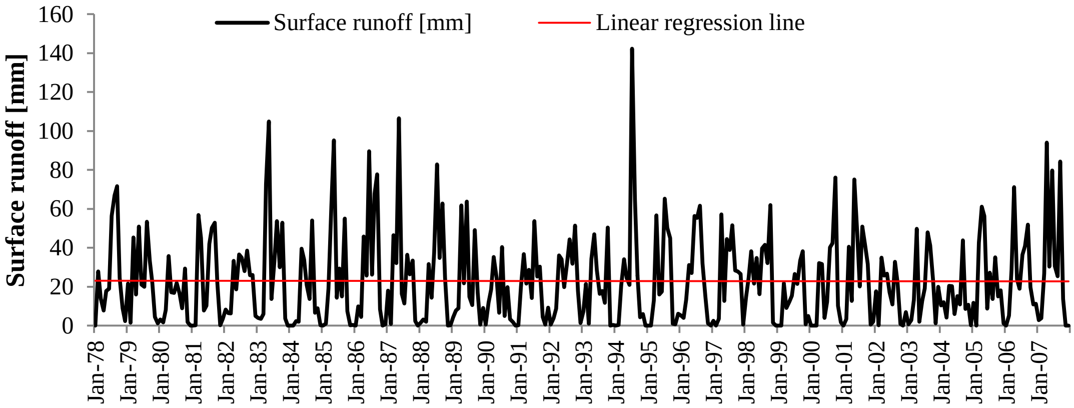

Figure 14: Mean monthly surface runoff [mm], Wondo Genet catchment, Ethiopia

The graph of Figure 15 shows the contribution of groundwater to the stream flow in the sub-catchment. There is a significant trend of increasing groundwater which is contributed to the stream flow, which can be related to exceeding soil water holding capacity rates. In relation to the decrease of average actual evapo-transpiration, it can be said that these two components are heavily related. As evapo-transpiration rates decline, the amount of water in the soil increases. When the amount of soil water exceeds the soil water capacity, more soil water will be removed from the soil and will contribute to the stream flow. This is mainly what happens in the Wondo Genet catchment; soil water capacity is limited, and thus the increased soil water due to decreased evapo-transpiration rates, is removed of the soil and contributes to the stream flow in the sub-catchment. This can imply an increase in discharge of river Tikur Wuha.

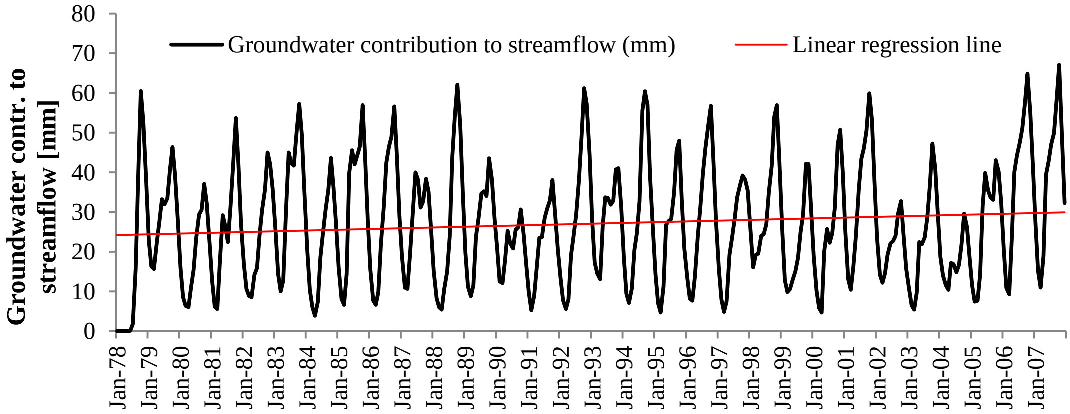

Figure 15: Mean monthly groundwater contribution to stream flow [mm], Wondo Genet catchment, Ethiopia.

Figure 16 presents the mean monthly sediment yield which is flowing out of the sub catchment. The figure shows almost no change in the modeling output of the sediment yield according to the linear regression line. This implies that there is no increased sediment yield flowing out of river Tikur Wuha, and thus there is no increased sedimentation in Lake Awassa.

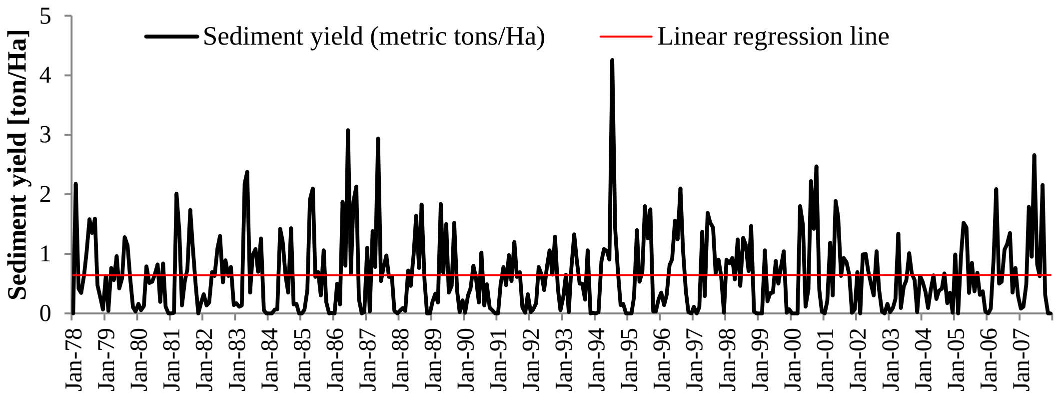

Figure 16: Mean monthly sediment yield [ton/Ha], Wondo Genet catchment, 1978 – 2007.

4.2.3 Hydrologic responses of land use types in the Wondo Genet catchment

Figure 17 shows the mean monthly actual evapo-transpiration (E_a) rates calculated by SWAT for the different land use types for the Wondo Genet catchment between 1978 and 2007. It shows that there are significant monthly differences between the land use types. Grassland and open bush land have almost the same E_a response; it varies between 100 mm/month in March and 55 mm/month in December. There are significant differences between small agricultural fields and large agricultural fields; the response of E_a varies for large agricultural fields between 100 mm/month in June and 30 mm/month in September, while the response of small agricultural fields varies between 55 mm/month in February and 20 mm/month in December. This can be the result of the different cropping systems; smallholder farms have intercropping systems with perennial crops, whereas large agricultural fields have a monoculture system with mainly crops as maize and potatoes. These crops have their growing season between April and November and the rest of the year the land is bare. The E_a rates of natural forest remain almost constant throughout the year; it varies between 60 and 80 mm/month and only drops to 40 mm/month in December. Ayenew (2003) showed a significant relation between altitude and daily E_a rates in the Rift Valley and the highlands in Ethiopia. This is not shown in this study;

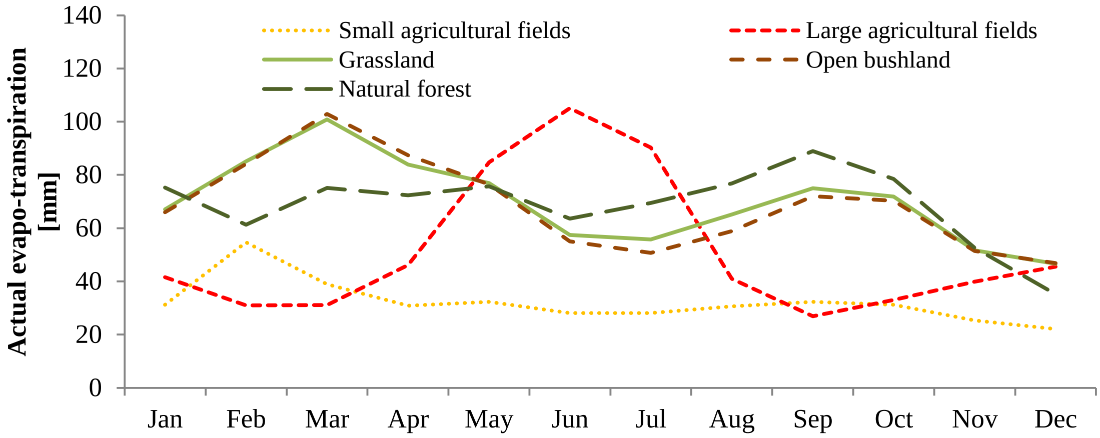

Figure 17: Mean monthly E_a [mm] rates (1978-2007) for each land use type, Wondo Genet catchment, Ethiopia.

however the upland area in this study is not part of the actual highland area, which lies at a higher elevation. Ayenew (2003) also showed that E_a is highly variable in the area around the Rift Valley due to changes in geology, topography, amount and distribution of rainfall and land cover.

The mean monthly surface runoff (SUR_Q, [mm]) within the Wondo Genet catchment varies from 0 to 45 mm/month. Figure 18 shows not much variation in SUR_Q [mm] between large and small agricultural fields, open bush land and grassland; it varies from 30 mm/month in September and drops to almost 0 mm/month between November and March. The SUR_Q of natural forest has the same pattern, although values are lower; max. 16 mm/month in September to almost 0 mm/month between November and March. Large agricultural fields land has the highest rates and variation in SUR_Q; one maximum of 35 mm/month in September and another maximum of 20 mm/month in May, between November and February it drops to almost 0 mm/month. These SUR_Q rates are mean rates per land use type for the whole catchment. This may imply that at some locations, for example on the steep slopes, SUR_Q values can be much higher, whereas values of SUR_Q within the lowland are always low. The trend of the SUR_Q curves is similar to those of the precipitation; the SUR_Q is a response on the amount and distribution of precipitation.

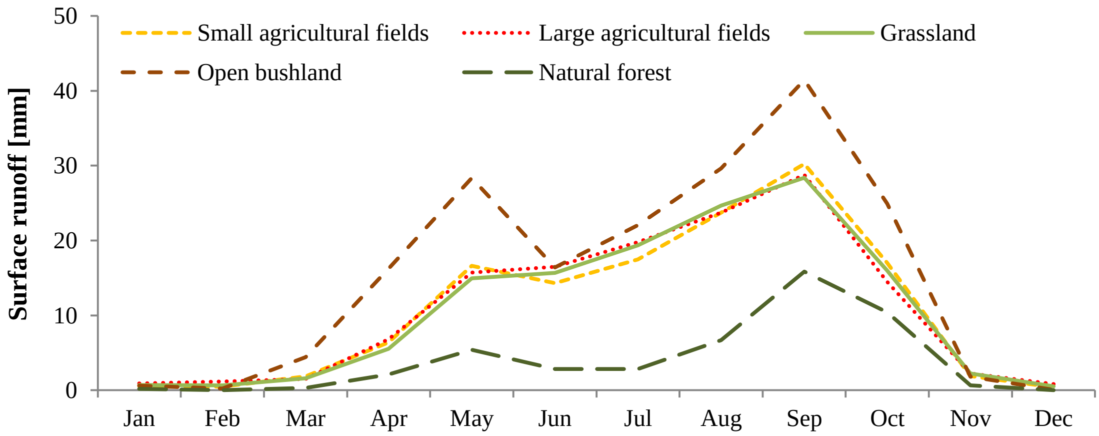

Figure 18: Mean monthly surface runoff (SURQ [mm]) rates (1978-2007) for each land use type, Wondo Genet catchment, Ethiopia.

Figure 19: A farmer stands before a new planted tree.

Descheemaeker et al., (2006) showed that rehabilitation of natural vegetation on steep hill slopes in the Tigray highlands (Ethiopia) resulted in significant decrease in surface runoff. Vegetation cover is one of the main factors which influence surface runoff. When the vegetation cover exceeds 65%, runoff becomes negligible. So it is highly important for the Wondo Genet catchment to preserve the remaining forest in the rift escarpment. In the Wondo Genet catchment there a few plots where forest habilitation is done, by planting new threes on logged slopes (Figure 19).

Mean sediment yield [ton/Ha] over the whole Wondo Genet catchment does not change in the period 1978-2007 (figure 16), but the sediment yield [ton/Ha] generated in the Wondo Genet catchment between the land use types does change. Figure 20 shows the mean and maximum sediment yield [ton/Ha] generated by each land use type per month over the period 1978-2007. Sediment yield generated by grassland, open bush land and natural forest is low; between May and December it is almost zero (Figure 20A). Small and large agricultural fields generate all year round sediment; small agricultural fields have two maximums, which are related to the rain seasons. Large agricultural fields generate on average 0.7 ton/Ha/month. The graph of the maximum sediment yield [ton/Ha/month] shows the same pattern but much larger values. This means that the range of sediment yield [ton/Ha/month] largely varies within the catchment.

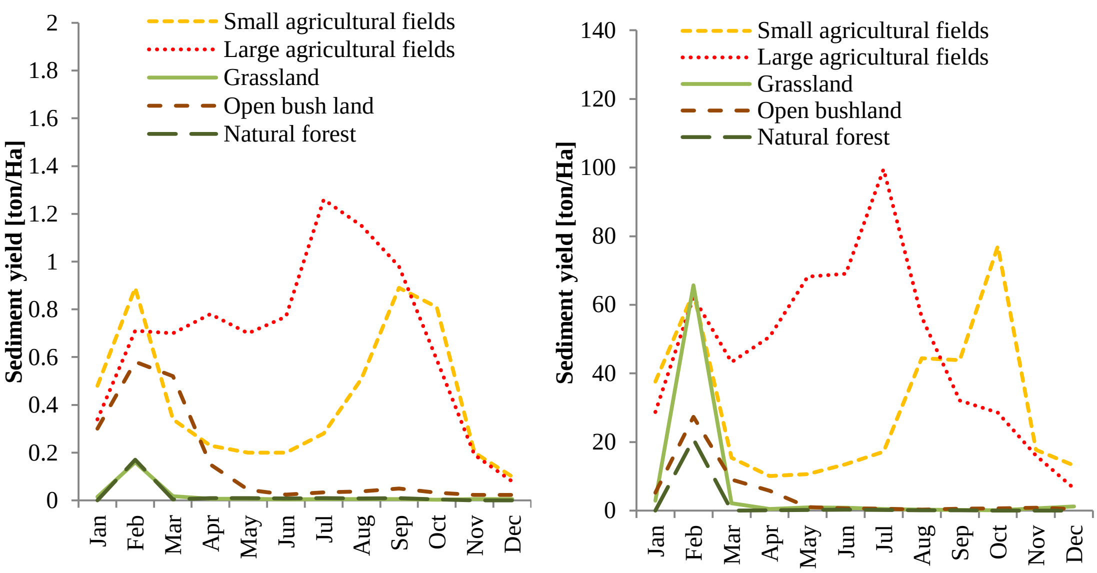

Figure 20: Mean sediment yield [ton/Ha/month] (A) and maximum sediment yield [ton/Ha/month] (B) for the Wondo Genet catchment, Ethiopia.

The mean sediment yield [ton/Ha/month] modeled by SWAT for each land use type and corresponding slope steepness is varying (Table 5). As Figure 20 also shows, natural forest, rangeland and open bush land generate not much sediment. However, all land use types generates more sediment with increasing slope steepness. According to table 5, large agricultural fields generate most of the sediment; mean sediment yield is 4.48 ton/Ha/month on the steepest slopes (>20%). Small size farmland generates more sediment than natural forest, rangeland and open bush land, but significant less than the large size farmlands.

Table 5: Mean sediment yield [ton/Ha/month] generated by each land use type and corresponding slope class, Wondo Genet catchment, Ethiopia.

Land use	Slope [%]				
	0-5	5-10	10-15	15-20	>20
Natural forest	- [A]	- [A]	0.00	0.01	0.04
Rangeland	0.02	0.06	0.09	0.09	0.27
Open bush land	0.02	0.05	0.08	0.11	0.23
Large size farmland	0.20	0.81	1.21	1.74	4.48
Small size farmland	0.06	0.17	0.22	0.28	0.78

[A] Land use type does not occur on the according slope class.

Old agricultural traditions can result in decreasing rates of infiltration and increasing rates of surface runoff and soil erosion. Multiple studies (e.g. Temesgen et al., 2012; Biazin et al., 2011) show that the traditional Ethiopian *Maresha* ploughing enhance soil evaporation and the reduction of infiltration rate, and thus increasing surface runoff. Most smallholder farms in the Wondo Genet catchment are still using the old ploughing techniques. Therefore it is necessary for local farmers to be aware of these results and the need to improve tillage technique for appropriate soil management techniques and better soil water conservation.

In the future, climate change can cause more dramatic effects on all hydrological elements in the catchment. Ficklin et al. (2009) modelled with SWAT the effects of climate change on the hydrological cycle; the results suggested that temperature change has significant effects on all hydrological elements. So there is a need for more extensive assessment of the potential climate change on the hydrology, especially in agricultural depended places where the need of water is vulnerable, such as the Wondo Genet catchment.

4 Conclusions

Extensive population growth occurred in Ethiopia during the last century, which has led people to move to the highly fertile soil in the Central Rift Valley of Ethiopia. Immigration in the Central Rift Valley caused major land use changes in this area during the last decades. As population grew, there was an increasing demand of arable and grazing land, as well as land available for smallholder settlement.

This study was done in the Wondo Genet catchment, which is part of the larger Lake Awassa catchment. The Wondo Genet catchment was also subject to many small settlements during the last decades, which resulted in major land use changes. Before immigration started, the Wondo Genet catchment consisted of extensive natural forest cover on the upland area and the rift escarpments. The lowland was mainly covered by Lake Cheleka and the swampy area around it. River Tikur Wuha drained water from this lake towards Lake Awassa. This study revealed the major land use changes between 1986 and 2011 by using Landsat satellite images. Classification of these images revealed forests dramatically declined between 1986 and 2011, which was mainly the result of (illegal) logging and smallholder settlement. Between 1986 and 1994 agricultural land extended, especially the small agricultural fields (< 2 Ha) on steeper slopes, while the amount of rangeland declined. Between 1994 and 2011 the total amount of agricultural land did not extended much, but a significant part of the small agricultural fields (< 2 Ha) turned into large agricultural fields (> 2 Ha), which has more economical benefits. The water body (former Lake Cheleleka) did not change much between 1986 and 1994, but totally disappeared between 1994 and 2011. This is mainly the cause of irrigation in the upstream area and siltation due to the removal of the natural vegetation in the upstream area.

Measured data of river Tikur Wuha revealed an increase in discharge during the last 30 years. Together with the disappearing of Lake Cheleleka, it is argued that there have been major hydrological changes in the Wondo Genet catchment. Mean monthly precipitation rates in the catchment showed no significant changes which can be related to the hydrological changes. Modeling the hydrological balance components with the SWAT model revealed that the actual evapo-transpiration rates and the groundwater contribution to the stream flow significantly changed during the study period. Actual evapo-transpiration rates declined what caused an increase in soil water content. However, the soil water holding capacity is limited, and thus soil water is removed of the soil and contributing to the stream flow. The average surface runoff in the Wondo Genet catchment did not change much, so it is likely to say that the decrease in actual evapo-transpiration rates caused the increase in discharge of river Tikur Wuha. This is also related to the land use changes in the same study period; the actual evapo-transpiration rates for agricultural land use are lower than for natural vegetated land use types. Thus, the increase in agricultural land use has led to a decrease in evapo-transpiration and therefore, in an increase in stream flow.

This study showed the effect of land use changes on the hydrology in the Wondo Genet catchment. Lake Cheleka disappeared and turned into a swamp area. Sediment yields generated by agricultural fields are much higher than for natural vegetated land use types. This has caused sedimentation in Lake Cheleleka which therefore dried up. Currently the swamp still acts as a sediment and water trap, but with more sediment which will settle down in the swamp in the future, the swamp has not got storage capacity for sediments and water anymore. This can result in more sediment and water outflow into Lake Awassa, which will enhance the rising of Lake Awassa and causing more problems to Awassa town and the people who live here.

More detailed studies are needed for further research to the hydrological changes in the Wondo Genet catchment and its relation to the water level rise of Lake Awassa. More data for calibration is needed to have more accurate outputs of the SWAT model. Especially more research can be done to the different land use types in the catchment, to have more detailed hydrological responses of these dominant land use types.

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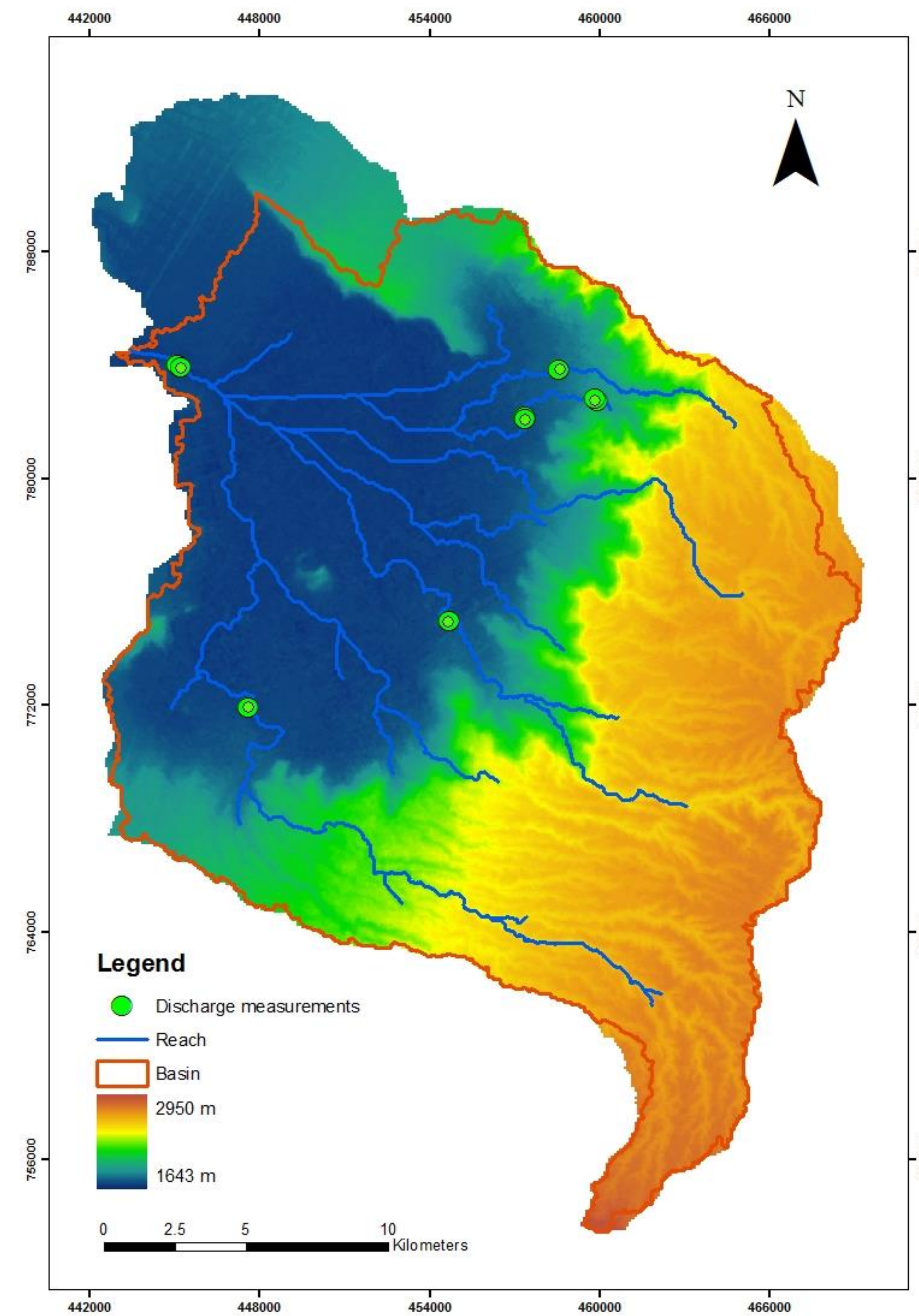
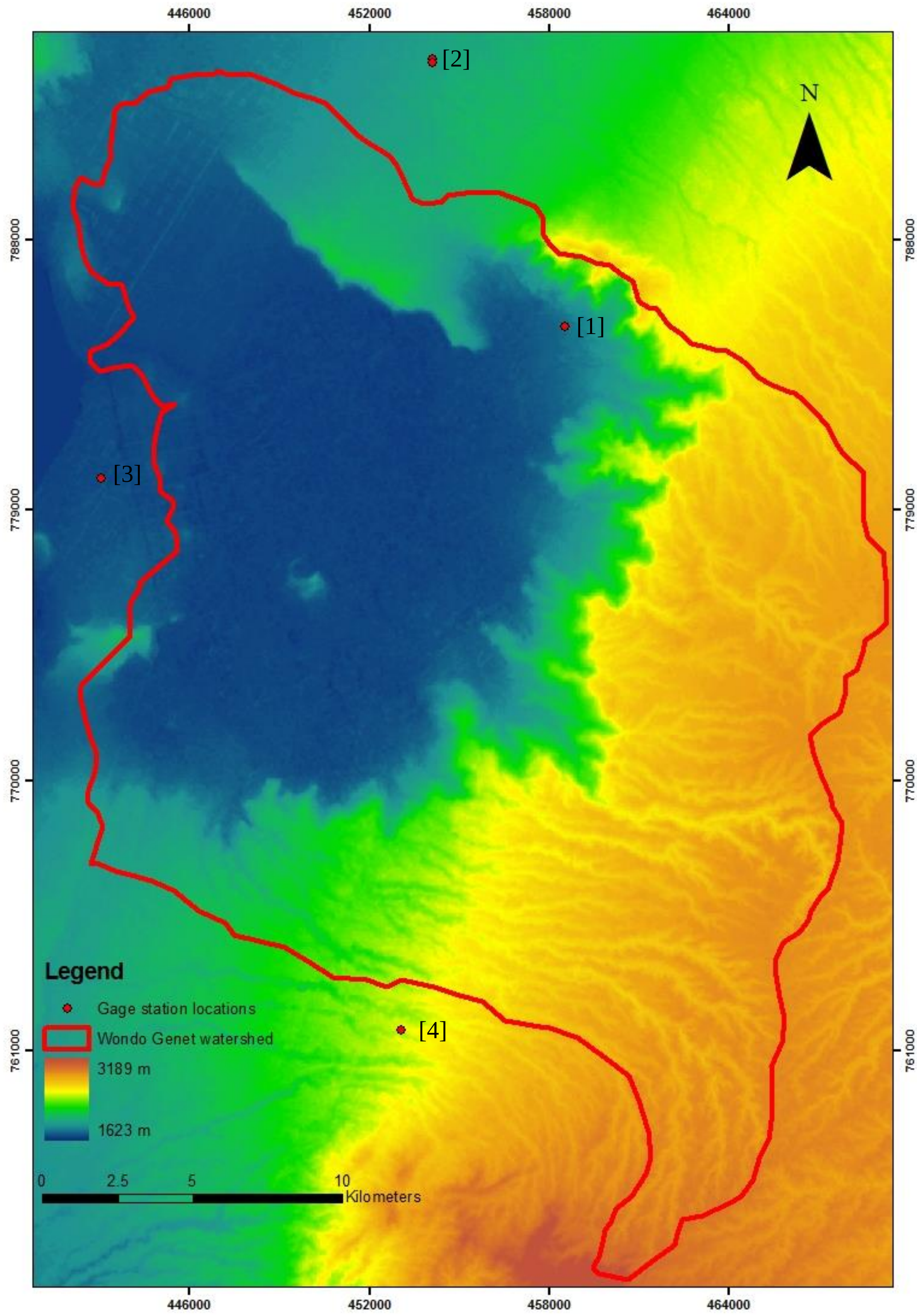
Appendix 1 – Locations of stream flow measurements



Appendix 2 – Weather gage station locations



Appendix 3 - Total land use change

		Change between 1986 – 1994 (%)	Change between 1994 – 2011 (%)
Open bush land	**Open bush land**	**95**	**99**
	Natural forest	5	1
Natural forest	**Natural forest**	**47**	**30**
	Open bushland	45	18
	Large agr. fields	1	11
	Small agr. fields	4	29
	Grassland	3	12
Grassland	**Grassland**	**26**	**58**
	Natural forest	2	0
	Large agr. fields	31	17
	Small agr. fields	40	13
	Wetland	1	12
Large agricultural fields	**Large agr. fields**	**68**	**59**
	Small agr. fields	24	23
	Grassland	5	12
	Wetland	3	6
Small agricultural fields	**Small agr. fields**	**63**	**32**
	Forest	15	3
	Large agr. fields	10	44
	Grassland	6	7
	Wetland	6	14
Wetland	**Wetland**	**62**	**67**
	Large agr. fields	8	6
	Small agr. fields	29	11
	Grassland	3	16
Water	**Water**	**60**	**0**
	Small agr. Fields	8	0
	Large agr. fields	4	0
	Wetland	28	100

Appendix 4 – Observed precipitation for the different gage stations (1978-2007).