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Watershed Hydrological Responses to Changes in Land Use and Land Cover, and Management Practices at Hare Watershed, Ethiopia

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ABSTRACT

This study investigates hydrological responses to changes in land use, land cover and management practices at Hare River watershed, Southern Rift Valley Lakes Basin, Ethiopia. It addresses methods that are required to better characterize impacts of land use and cover and climate change scenarios and understand the upstream-downstream linkages with respect to irrigation water allocation. Understanding how the changes in land use and cover influence streamflow and subsequently optimization of available water resources utilization can enhance the ability of planners, practitioners, researchers and farmers to formulate and implement sound policies to minimize undesirable future impacts and devise management alternatives.

Three land use and cover maps were developed using aerial photographs and satellite image through visual interpretation of the aerial photographs and supervised classification of the satellite image. The rates of land use and land cover changes were identified for two periods at watershed and sub-watershed levels. Two physical-based, semi-distributed hydrological models, SWAT2005/ArcSWAT and HSPF, were utilized to simulate hydrological responses to land use and climatic changes. Streamflow data at the outlet of the watershed was utilized to analyze seasonal stream flow variability due to land use and land cover changes. The performances of the models have been evaluated through sensitivity analysis, calibration, validation and uncertainty analysis. Consequently, impacts of hypothetical land use and climate change scenarios were developed to analyze their impacts on downstream water users. Eventually, based on the results these scenario analyses a new optimal irrigation water allocation tool was developed to allocate available water resources among competing irrigation sites.

The results of the land use and land cover change analysis identified that farmlands and settlements class has expanded during the past four decades. Detailed impacts of these changes were analyzed employing the SWAT2005. Sensitivity analysis using the SWAT2005 model has pointed out some crucial parameters that control the surface and subsurface hydrological processes of the studied watershed. Consequently, results of the models performances assessment illustrated that both SWAT2005 and HSPF have resulted acceptable outputs with some efforts of acquiring data in areas where there is limited available data. However, the SWAT2005 model performs slightly better than HSPF for monthly and

seasonal streamflow analysis. As a result, streamflow variability during the dry and wet seasons was further analysed using this model based on pre-identified scenarios. Furthermore, uncertainty analyses were performed and discussed using ParaSol, SUNGLASSES, SUFI-2 and GLUE methods. On the other hand, results from the climate change scenario analysis using GCM for the period of 2010-2099 showed that an increase in future average annual precipitation and average temperature when compared to the baseline period. Similarly, analysis made on intervention of small scale irrigation in the upper and middle reach of the watershed resulted in substantial decrease in mean monthly discharge during the dry season, while increased discharge during the wet season.

Consequently, an optimal tool was developed to allocate scarce water resources among three upstream and downstream demand sites with a prime objective of achieving equitable resources utilization while maintaining acceptable economic efficiency and environmental sustainability. The analysis revealed that a substantial volume of water can be saved through deficit irrigation principles. It is also noted that, in the face of intense competition among irrigation water users where there is a significant water shortage throughout a watershed, equitable and efficient utilization of water resources has always remained a social goal.

The developed tool can be used in other watersheds too by decision makers and planners where there exist irrigation water allocation problems between competing upstream and downstream irrigation sites. However, it needs simulation outputs from SWAT2005 and needs to specify the exact sub-watersheds where the irrigation sites are located. In order to utilize outputs from other models, the tool needs some modification in the algorithm (visual basic) specifically on the declaration of the input files. Generally, the results highlighted that use of an integrated simulation-optimization approach has a paramount importance to investigate impacts of land use and cover and climate change on hydrological regime and consequently allocate limited available water resource in an equitable manner among competing sites.

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LIST OF ABBREVIATIONS

ACB	Abaya-Chamo Basin
BASINS	Better Assessment Science Integrating Point and Nonpoint Sources
BMP	Best-management practices.
CASC2D	CASCade of planes in 2-Dimensions
CIA	Central Intelligence Agency
CSA	Central Statistics Agency
CREAMS	Chemicals, Runoff, and Erosion from Agricultural Management Systems
CV	Coefficent of Variation
DEM	Digital Elevation Model
DJF	December January February
DWSM	Dynamic Watershed Simulation Model
EPIC	Environmental Impact Policy Climate
EU	European Union
FAO	Food and Agriculture Organization of the United Nations
GCM	Global Climate Model
GenScn	GENeration and analysis of model simulation SCeNarios
GHGs	Greenhouse Gases
GIS	Geographical Information System
GLEAMS	Groundwater Loading Effects on Agricultural system
GLUE	Generalized Likelihood uncertainty analysis Extension
GCP	Ground Control Points
GPS	Global Position System
HadCM3	Hadley Centre for Climate Prediction and Research Coupled Model, UK
HBV	Hydrologisika Bayraans Vattenbalans-avediling
HEC-HMS	Hydraulic Engineering Centre- Hydrologic Modeling System
HRU	Hydrological Response Units
HSPEXP	Expert System for HSPF hydrology calibration
HSPF	Hydrological Simulation Program-FORTRAN
IMPLND	HSPF parameter for Impervious Land
IPCC	Intergovernmental Panel on Climate Change
IUCN	International Union for Conservation of Nature
IWRM	Integrated Water Resources Management
IWMI	International Water Management Institute
IHACRES	Identification of unit Hydrographs and Component flows from Rainfalls, Evaporation and Streamflow data
LH-OAT	Latin Hypercube sampling-One-Factor-At-a-Time
LUCC	Land Use and Land Cover Changes
MAM	March April May
MIKE SHE	European Hydrological System model (From Danish Hydraulic Institute)
MoWR	Ministry of Water Resources
NCEP	National Centre for Environmental Prediction
ParaSOL	Parameter Solution
PERLND	HSPF parameter for Pervious Land
PRMS	Precipitation-Runoff Modeling System
TOPLATS	TOPMODEL-based Land Atmosphere Transfer Scheme

TOPMODEL	Topographic Model
RCHRES	Stream Reaches
RCM	Regional Climate Model
SCE-UA	Shuffled Complex Evolution algorithm-University of Arizona
SCS	Soil Conservation Service
SDSM	Statistical DownScaling Model
SPI	Standard Precipitation Index
SRES	Special Report on Emission Scenarios
SSI	Small Scale Irrigation
SUFI-2	Sequential Uncertainty Fitting-ver.2
SUNGLASSES	Sources of UNcertainty GLobal Assessment using Split SamplES
SWAT	Soil and Water Assessment Tool
SWRRB	Simulator for Water Resources in Rural Basins
UCI	User control input
US-ACE	United States- Army Corps of Engineers
USDA-ARS	United States Department of Agriculture- Agricultural Research Service
UTM	Universal Transverse Mercator
WASIM	Water balance Simulation Model
WATBAL	Water Balance Model
WDM	Watershed Data Management
WDMUtil	Watershed Data Management Utility
WFI	With Full Irrigation scenario
WinHSPF	Windows version of HSPF
WOI	With Out Irrigation scenario
WRM	Water Resources Management
WTI	With Target Irrigation scenario
WSSD	World Summit on Sustainable Development

LIST OF NOMENCLATURES

A_{Ei}	Application efficiency (%)
AGWO	HSPF parameter for active groundwater outflow (in/interval),
A_i	Crop area (ha)
Alpha_BF	Baseflow alpha factor (days)
$Aq_{sh,}$	shallow aquifer storage (mm)
CEC	Cation Exchange Capacity (meq/100g)
CN	Curve Number
CWD	Crop water demand for the given day (m^3)
DELT60	HSPF parameter for number of hr per interval (hr/interval)
EL_b	Mean elevation in the elevation band (m)
EL_g	Elevation at the recording gage (m)
E_{NS}	Nash-Sutcliffe model efficiency
ESCO	Soil Evaporation Compensation Factor
ET_a	Actual evapotranspiration (mm)
ET_p (PET)	Potential evapotranspiration (mm)
ET_t	Target evapotranspiration (mm)
FC_{ly}	Water content of the soil layer at field capacity (mm)
GW_delay	Groundwater delay (days)
GWVS	HSPF parameter for index to groundwater slope (inches)
I_a	Initial abstraction (mm)
KGW	HSPF parameter for groundwater outflow recession parameter (/interval),
K_s	Saturated hydraulic conductivity for the layer ($mm \cdot hrs^{-1}$).
Ky	Crop yield response factor
LATQ	Lateral flow (mm)
LZSN	HSPF parameter for Lower Zone Nominal Storage (mm)
Q_g	Groundwater flow or base flow, into the main channel (mm),
Q_l	Lateral flow (mm d^{-1})
q_{obs}	Observed daily discharge in (m^3s^{-1})
q_{sim}	Simulated daily discharge (m^3s^{-1})
Q_s	Amount of surface runoff on day i (mm)
R_b	Rainfall falling in the elevation band (mm)
R_d	Rainfall recorded at the gage (mm)
R_l	Rainfall lapse rate (mm/km)
S	Potential maximum moisture retention after runoff begins (mm)
SLOPE	Average slope steepness (m/m)
SOL_AWC	Soil Available Water Content (mm/mm)
SOL_BD	Soil Bulk Density (Mg/m^3)
SOL_EC	Soil electrical conductivity (ds/m)
SOL_K	Soil Hydraulic Conductivity (mm/hrs)
SOL_OC	Soil Organic Content (%)
SPI	Standard Precipitation Index
SURO	HSPF parameter for surface outflow (in/interval)
SURQ	Surface runoff (mm)
SURSE	HSPF parameter for equilibrium surface detention storage (in)
SURSM	HSPF parameter for mean surface detention storage over the time interval (in)

SW_0	Initial soil water content (mm)
SW_t	Final soil water content (mm)
TI	Target Irrigation (mm)
TT_p	Travel time for percolation (hrs),
UZSN	HSPF parameter for Upper Zone Nominal Storage (mm)
V_k	Quantity of water available at each sub-watershed (m^3)
W_d	Amount of water percolating from the shallow aquifer into deep aquifer (mm)
$W_{p,ly}$	Amount of water percolating to the underlying soil layer on a given day (mm)
W_{rec}	Recharge entering the aquifer (mm)
W_s	Amount of percolation exiting the soil profile bottom (mm)
WUE	Water Use Efficiency (%)
WU_{sa}	Water use from the shallow aquifer (mm)
WYLD	Water Yield (streamflow, mm)
Y_a	Actual crop yield (kg)
Y_m	Maximum Crop Yield (kg)
Y_t	Targeted Crop Yield (kg)
ϕ_d	Drainable porosity (mm/mm),

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CHAPTER 1

Introduction

1.1 Background and Problem Statement

An understanding of hydrological processes is essential for investigating impacts of land use and land cover, and climate changes on water resources. Hydrologic response to changes in Land Use and Cover Changes (LUCC), land management practices and climate changes is an integrated indicator of watershed condition. Watersheds are generally considered as useful units of analysis and action because of several ***physical*** (Natural system, multiple scales, ideal for process studies, integrated framework, assist in addressing complexity) and ***social*** (decision-making tool, social organization, upstream and downstream links) characteristics (Schreier et al. 2003; Richard B., 2005).

Hydrologic modeling and water resources management studies are intrinsically related to the spatial processes of the hydrologic cycle. Land use and land cover influences watershed hydrological responses by partitioning rainfall between return flow to the atmosphere as evaporation and transpiration and flow to aquifers and rivers. However, techniques for the analysis of the impact of LUCC on modeled hydrological responses are still very much at early stage. The prediction of the effect of future change (and validation of prediction) has hardly even started (Beven, 2001).

Water is the principal motivating and integrating factor in hydrologic response studies. The concept of a watershed inherently integrates the ‘upstream’ with the ‘downstream’ through the flow of this central resource as part of the general hydrological cycle. A number of villages in a watershed often share the same stream as their water source. However, stream flow usually has high seasonal variability, and seasonal local water scarcity is a problem faced by many farmers in small watersheds (Jamtsho and Gyamtsho 2003). Furthermore, variability in stream flow produced by complex interactions of land use, land management, and climate, combined with competing and increased demand, make management of water resources at watershed scales extremely challenging and requires a thorough understanding of these interactions.

Given that impacts of LUCC on water resources are the result of complex interactions between diverse site specific factors and offsite conditions, standardized types of responses will rarely be adequate. General statements about land–water interactions need to be continuously questioned to determine whether they represent the best available information and whose interests they support in decision-making processes (FAO, 2002; Bewket and Sterk, 2004).

Though, Ethiopia is endowed with a substantial amount of water resources that can be of help for agricultural production, domestic use, and hydropower generation, a number of factors have affected the development and management of water sector in the country (EWSS, 2001). Thus, the overall aim of the country's water resources policy is to enhance and promote all national efforts towards the efficient, equitable, and optimum utilization of the available water resource for significant socio-economic development on substantial basis. On the other hand, the country is the second most populous country in Africa, which is under continuous growth rate during the past decades (Awulachew et al. 2005). Due to the rapid population growth and lack of proper land management practices, conversion of vegetation into agricultural land is increasing. These growing populations posed serious challenges in simultaneously meeting food requirements and dramatic water demand in future.

Consequently, there is an increasing need in Ethiopia to identify land-water linkages that helps for optimal utilization and management of available water resources. This is especially true in areas where there is considerable land use and land cover changes and high competition of water resources between upstream and downstream water users. As a result, integrated research approach that focuses on solving these problems is crucial for sustainable water resources development. Nevertheless, effective utilization and management of the water resources require detecting and simulating impacts of land use and cover changes and management practices on hydrological regimes and its effect on water availability at downstream water users. In addition, it requires optimizing the allocation of available water resources among competing upstream and downstream water users.

In recent years there has been an increasing recognition for the need of a new approach to the management of land and water resources, aimed at long-term sustainable utilization of natural resources, and the maintenance of the quality of the natural environment (Tanik, et al., 2003).

Understanding how LUCCs influence stream flow will enable planners to formulate policies towards minimizing the undesirable effects of future land use changes on stream flow pattern. Furthermore, future LUCC together with climate change scenarios can cause significant impacts on water resources by resulting changes in the hydrological cycle. However, in order to predict the future effects of LUCC on river flow, it is important to have an understanding of the effects historic LUCCs have had on river flow. Besides, the knowledge of the types and impacts of land use and land cover, and climate changes is essential indicator for resource base analysis and development of effective and appropriate response strategies for sustainable management of natural resources.

Moreover, Smith and Kivumbi, (2002) argued that limited water resources and growing competition for water in a rural watershed will reduce its availability for agricultural use. Conversely, the need to meet the growing demand for food will require increased crop production from less water. In addition, Shah and Strong, (2000) suggested that water scarcity is potentially the most serious obstacle to 'food security, poverty reduction and protection of the environment' and is likely to affect one-quarter of the world's population within the next 25 years. Therefore, achieving greater productivity of water will be a primary challenge for the near future and needs to employ techniques and practices that assist to utilize available water optimally and in an equitable manner in a watershed system.

A simulation-optimization approach can overcome the above problems. Simulation models are indispensable instruments for studying responses of the hydrological regime to various land use and climate change scenarios, and land management options if they are built on a sound understanding of the hydrological processes (Miller et al, 2002; Singh and Woolhiser, 2002). On the other hand, optimization models are useful tools to optimise irrigation water allocations among competing sites based on objectives and constraints. Recently there is a trend of coupling simulation models with optimization tools in such a way that outputs from a simulation model can be used as inputs for the optimization program. The outcome of such integrated approach can significantly enhance the ability of planners, practitioners, and researchers to devise watershed management alternatives.

1.2 Objectives of the Study

This study aims to develop an irrigation water allocation tool that would help to better understand and optimize available limited water resources utilization strategies among upstream-downstream competing irrigation sites. To satisfy this major objective, first impact of LUCC and climate changes on hydrological regime, and upstream-downstream linkages with respect to irrigation water use was investigated. Focus was given to investigate and analyze the spatio-temporal information on the status of LUCCs, watershed management practices and associated stream flow variability. The study also addresses the impacts of predefined land use, and management practices and climate change scenarios on hydrological regime.

The specific objectives are:

1) Develop an irrigation water allocation tool that enables optimal use of scarce water resource among competing upstream and downstream irrigation demand sites
2) Examine the extent of past land use and land cover changes and subsequently develop a method to evaluate impacts these changes on hydrological regime at watershed and sub-watersheds level
3) Evaluate the hydrological performance of two models through autocalibration-sensitivity analysis procedure and carryout uncertainty analysis in areas where there is limited available data
4) Identify climatic and land use and land cover change scenarios and analyse their effect on upstream-downstream irrigation water use linkages

1.3 Significance of the Study

The importance of investigating LUCCs and their impacts as a baseline requirement for land use planning and sustainable management of natural resources has been highlighted by many researchers (Brandon *et al*, 1998; Verburg et al., 1999; Petit *et al*, 2001; Read *et al*, 2002). These scientists have argued that more focused management intervention requires information on the rates and the impacts of LUCC as well as the distribution of these changes in space and over time. Moreover, LUCC has significant impacts on the functioning of socioeconomic and environmental systems with important tradeoffs for sustainability, food security, biodiversity and the vulnerability of people and ecosystems to global change impacts. However, to predict the future effects of land use and cover and climate change on streamflow, it is important to have an understanding of the effects historic LUCC have had on the hydrological regime.

In Ethiopia, most parts of the regions face treats concerning food production that mostly affects the rural livelihood mainly due to increase in population on one hand and inappropriate resources management on the other hand. Previously, there have been some efforts made at the study area, Hare watershed (Seleshi, 2001; Krause, et al., (2004); Abel, 2005; Belete, 2007). However, there is no systematic research on techniques that deal with optimal irrigation water allocation among competing sites and impact analysis of LUCCs and climate change on hydrological regime at a watershed level and sub-watershed level at the study area in particular and in Ethiopia at large. Nevertheless, there have been many great efforts elsewhere in LUCC analysis and their impact analysis at a watershed level. Furthermore, there have been independent efforts either to simulate impacts of LUCC on streamflow or optimize irrigation water allocation among competing sites. But, there has been much less focus on the combined use of simulation-optimization approach where the information from simulating a hydrological model is used as input for an optimization model for optimal allocation of irrigation water.

Accordingly, an integrated simulation-optimization approach that takes in to account optimization of irrigation water allocation among competing sites, LUCCs analysis, prediction of the impacts of different climatic and land use and management scenarios will have a paramount importance in the development of sustainable land and water use strategic plans. Understanding the types and impacts of LUCC is an essential indicator for resource base analysis and development of effective and appropriate response strategies for sustainable management of natural resources in the country in general and at the study area in particular.

Therefore, the contribution of this research is a newly developed decision support tool with the objective of allocating limited available water among upstream and downstream competing crops and irrigation sites based on a simulation-optimization approach. Moreover, it presents a method to quantify LUCCs and their impact on hydrological regime. This has been achieved through a method that combines two physical-based, semi-distributed hydrological models (SWAT2005 and HSPF) to simulate the hydrological processes, Geographical Information

System and use of remote sensed data interpreted to detect and analyse LUCC. In addition, information on future regional changes in climate and possible scenarios and policy implications are provided since there is a strong concern over the impacts of future climate changes on the agricultural production in Ethiopia.

1.4 Organization of the Thesis

The thesis is organized in eight chapters: Chapter 1 is an introduction chapter where the background, problem statement, objectives and significant of the study are discussed. In Chapter 2, descriptions of the study area are elucidated in detail. Concepts of Land use and Land cover changes, methods data acquisition, detection and quantification of LUCCs and analysis made at watershed and sub-watershed levels are elaborated in Chapter 3. Chapter 4 describes watershed hydrological modelling in the context of sustainable water resources. It highlights water resources management, discusses guidelines for model selection, and describes selected hydrological models for this research and the processes modelled. It further discusses on processing and preliminary analysis of input data for the models.

In Chapter 5, the performance of the selected hydrological models is assessed through sensitivity analysis, calibration, validation and uncertainty analysis. Simulations of hydrological responses to LUCC are elaborated in Chapter 6. In this chapter first impact of LUCC on the hydrological regime in past and present were analysed and then future land use and climate change scenarios were developed and examined. In Chapter 7, an integrated simulation-optimization approach is discussed with the objective of utilizing limited available water among competing irrigation sites in a watershed. Here, the procedures to develop irrigation water allocation tool and results of optimized irrigation water allocation are elaborated. Finally, in Chapter 8, conclusions and recommendations are provided.

1.5 Overall Framework of the Study

The method to evaluate the impacts of land use and land cover changes, land management practices and climate change on hydrological regimes can be achieved through integrating GIS, remote sensing, and hydrological models. Advances in computing have allowed distributed watershed models to perform hydrologic simulation with reasonable resolution at a more detailed level. LUCCs delivered by repeated aerial photography and satellite images greatly contribute to planning and management of available resources, especially in the watersheds where other kinds of background data are often lacking. Specifically, LUCC information is of critical importance in hydrologic modelling, as it helps determine model variables that account for the volume, timing, and quality of runoff.

A Physically-based distributed hydrological model that allows several different subunits or objects to be defined within a watershed is utilized. Simulation of the model offers outputs that assist to integrate our knowledge of hydrologic systems to the real world hydrologic processes. On the other hand, in order to assess and integrate the impact of climate change, Global Climate Model was employed to develop climatic change scenarios for simulating future climatic conditions. For instance the use of SWAT2005 provides outputs that help to perform irrigation water use analysis in both a stochastic and deterministic manner, which is particularly useful in the estimation and projection of future agricultural water requirements under a variety of conditions.

This research therefore extends the integration of a hydrologic model SWAT2005 with a newly developed irrigation water allocation program to optimally allocate and use limited water resources among competing crops at three irrigation sites based upon future climate scenarios. The program can be used as decision support tool to determine irrigation water application depths in order to utilize available water in an equitable manner and maximize the returns from the entire watershed. Details of the approach followed are given in Figure 1.1.

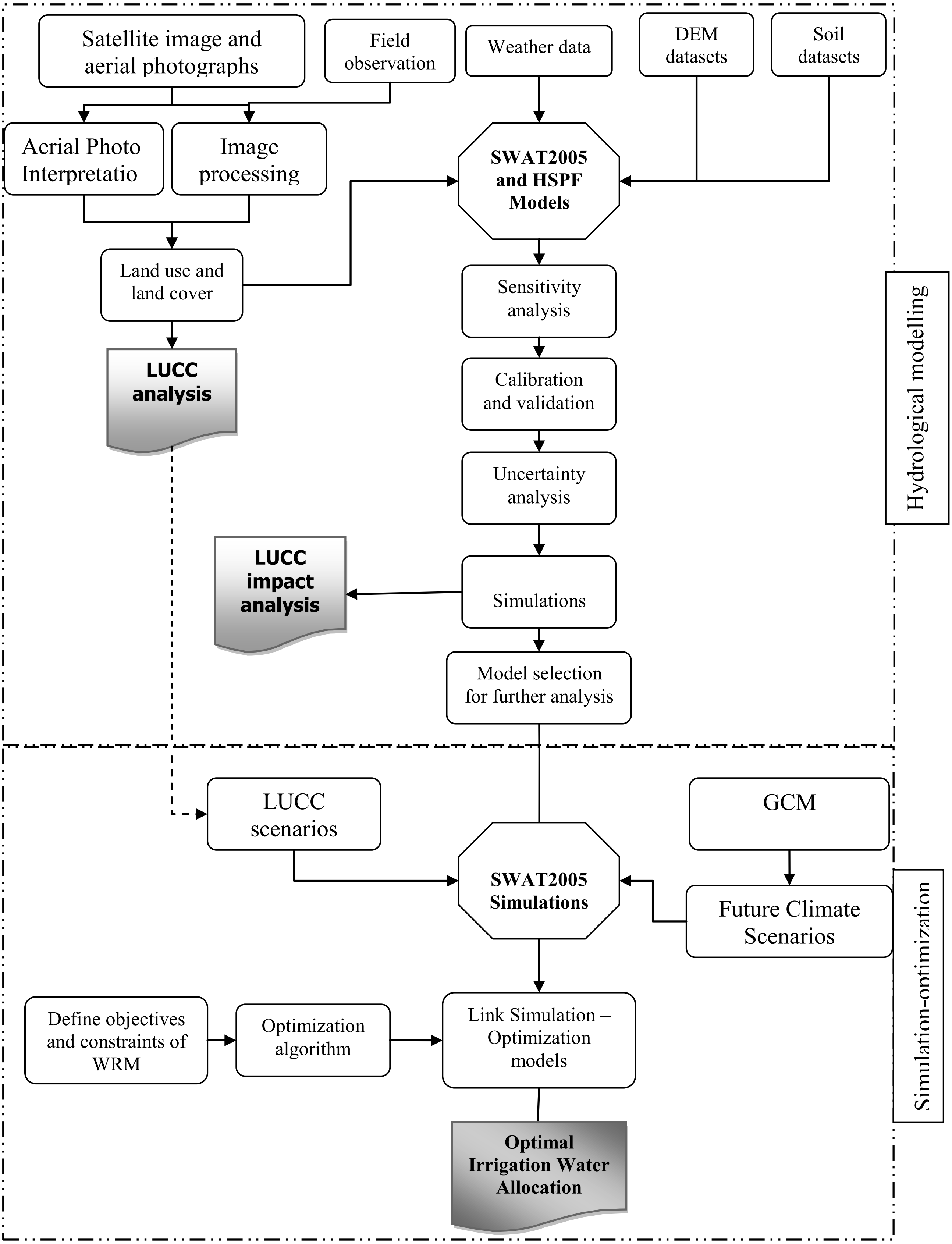


Figure 1.1 Flow chart of the research approach

CHAPTER 2

The Study Area

2.1 Location and Description

The study area, Hare River watershed, is located in the Abaya-Chamo sub-basin of the southern Ethiopian Rift Valley and drains to Lake Abaya, which is the second largest lake of the country. The watershed is situated between 37° 27‘and 37°37‘Eastern longitude and 6° 03‘and 6° 18‘northern latitude and has a land area of 182 km^2 where 85 % of the watershed is gauged before it joins Lake Abaya. Smallholder agriculture is the dominant land use in the watershed. Figure 2.1 provides the location of Hare watershed and elevation of the landscapes.

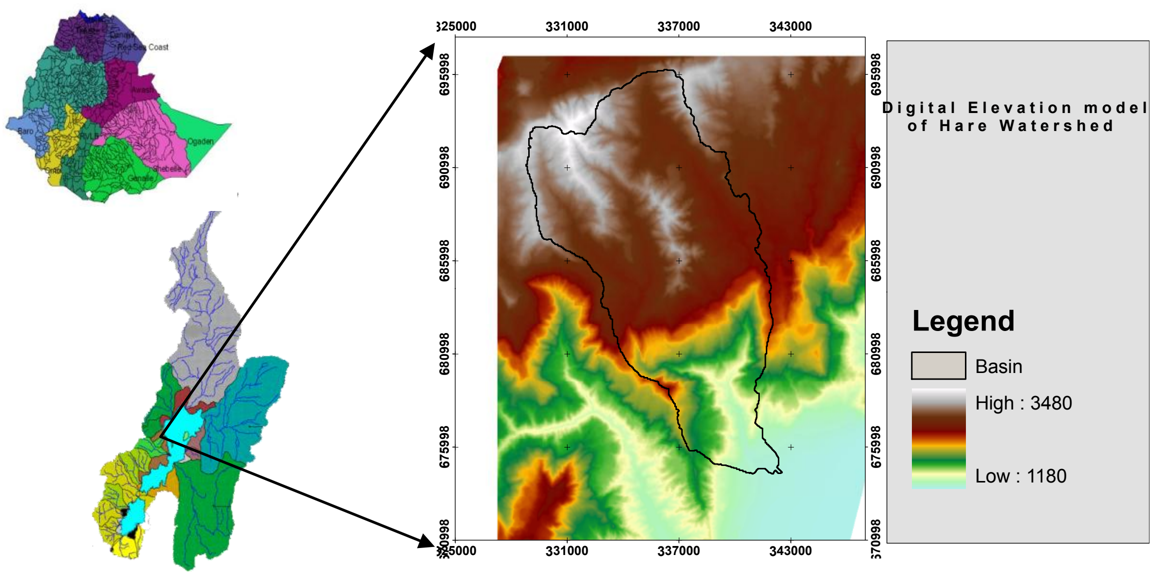


Figure 2. 1 Location of Hare Watershed

Hare watershed is selected as case study for this research because it represents watersheds where there is high competition for irrigation water use among upstream and downstream irrigation sites. In addition, it can be considered as representative watershed where there is high landscape and climatic zone difference within short distances. The population growth and land use systems together with considerable human interventions in the upper part of

Hare watershed makes it feasible for LUCC impact analysis on hydrological regime. Moreover, this dissertation is part of several investigations that have been carried out in the Abaya-Chamo Basin (ACB) within the context of enhancing research capacity on Integrated Water Resources Development Programme (Förch, 2007) that was funded by the German Research Foundation (DFG) and hence the research is closely linked to the results of the other research activities under the DFG project.

2.2 Topography, Geology and Soils

The topography of the study area is generally increasing in elevation from the downstream to the upstream. The middle reach of the watershed is mainly covered by steep slopes characterized through abrupt faults. As part of the Integrated Water Resources Development Programme, an international and interdisciplinary group of students conducted a study at Hare watershed in 2004 (Förch, 2007). Accordingly, Hare watershed can be divided into; highland valleys areas with moderate slopes and the (intersected) separating plateaus, unstable area with a high slope that has several spots of different inclinations caused by landslides, escarpment base (the southern part of the watershed area a region of two dividing ridges) and delta area (the area located between the escarpment base and Lake Abaya) Krause, et al., (2004).

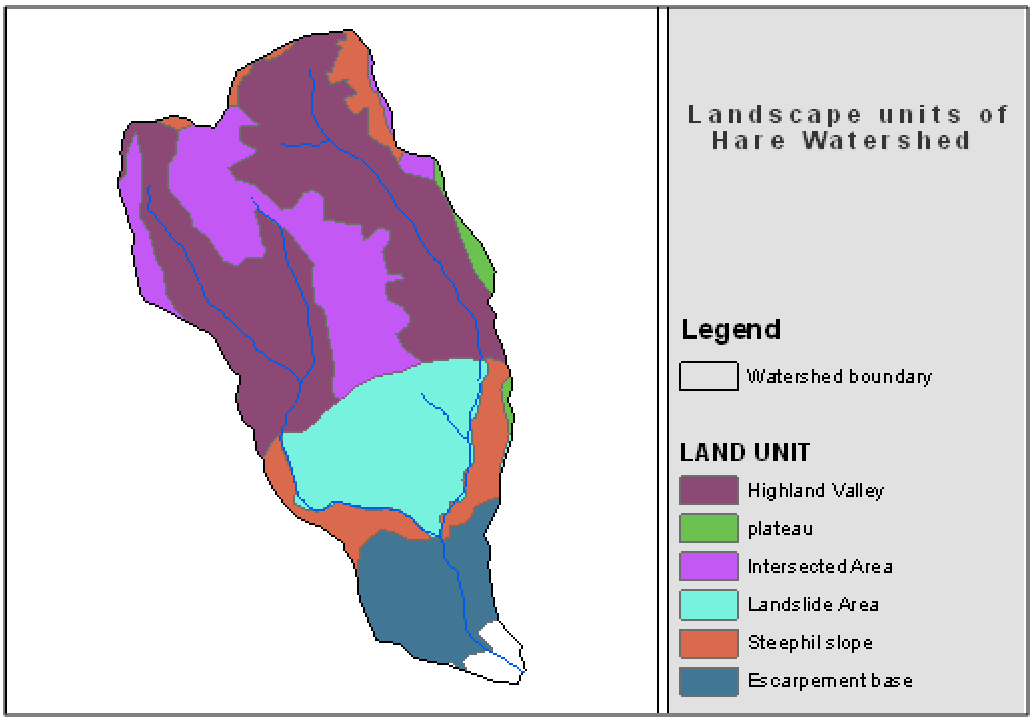


Figure 2. 2 Major Landscape units of Hare Watershed

There is limited information available on the geological formation of the study area. Accordingly, general geological information of the basin is used to describe the watershed. The geology of the country comprises a mixture of ancient crystalline basement rocks, volcanic rocks associated with the East African Rift system and sediments of various ages. The Hare watershed being part of the rift valley was formed by volcanic activities in the Rift Valley during the period of Pliocene and Holocene. This evidenced by Krause, et al., (2004) who sampled bedrock from Hare watershed that shows typical volcanic origin containing 25-40% quartz. Makin (1975) suggested that ancient basement rocks lie under the whole Rift Valley. They consist of gneisses, which transform into granites and grandiosities. Most of the middle and upper part of the watershed is covered with recent quaternary period Aden series, basaltic flows and related spatter cones. The area is, therefore, mainly characterized by volcanic rocks of tertiary and as well as with quaternary period alluvium deposits. The volcanic rocks around the aquifers could be fractured and thus yield modest amounts of water to wells and springs in the upper part of the watershed.

According to the FAO (1998b) and Krause, et al., (2004), the watershed can be characterized by four major soil types. The occurrence of different soil types is related to geology and the relief that has significant influence on the development of soil types. Most upper part of the watershed is covered by cambisols which are characterized by slight or moderate weathering of parent material so are young soils and suitable for agricultural practices. These soils are mostly brown in colour and have medium and fine-textured materials that could derived from a wide range of rocks, mostly in colluvial or aeolian deposits. Cambisols on steep slopes are best kept under forest. The second type is ferralsols that attribute to some parts of the high land valley areas with occasional spots in every land use classes except the upper dissected plateaus. These soils are deeply weathered that resulted in a high concentration of residual and have red or yellow colour. They have good physical properties but are chemically poor and hence are used for cultivation with fertilization.

Regosols are the third type of soils that cover very steep parts of the middle watershed and the lower foot are covered, which are highly erodible and can be characterized by constant disruption of mass movements and human activities. These soils are mostly stony and sandy clay loam in texture. The fourth types are fluvisols that are found at the alluvial river deposits of Harare and Gina-River where slopes are not too steep and the downstream part of the watershed. These are fertile soils and hence fertility decreases as on goes from the downstream to the upstream. In a previous study, Thiemann, (2006) determined the physical characters and erodibility of the soils at Bilate watershed (northern part of ACB) through sampling and analyses of soil horizons and layers of profiles. Accordingly, the major soils groups in the Bilate watershed are nitisols and luvisols in the highlands, whereas vertisols and cambisols dominate in the Rift Valley.

2.3 Hydro-Meteorological Settings

Hare river Morphological parameters

Rivers can be divided into three zones: the headwater stream zone, middle-order zone and lowland zone. Hare River displays characteristics of each of these zones. Its morphological characteristics including watershed platform, shape factors and watershed area factors make the watershed as a typical watershed in the mountainous area of Ethiopia.

Table 2.1 provides the definition of morphological parameters of Hare watershed. The parameters were measured from DEM, stream networking, and delineated watershed using ArcGIS tools and further processed to compute important morphological parameters. The procedure adopted by Abel (2005) was modified and employed here to characterize the watershed.

Table 2.1 Definition of Morphological Parameters

Description	*Symbol*	*Measured value*
Watershed Area	A_E	182 Km^2
Elevation at Abaya lake shore	H_{min}	1180m a.s.l
Elevation at the source of the River	H_{max}	3480m a.s.l
Length of Watershed Area (between H_{min} and P_{max}) (Length of the main drainage ditch, (I_f)	L_E	27.74 Km
Perimeter of the watershed	U_E	65.3 Km

Table 2.2 Computed values of morphological Parameter

Parameter	***Equation***	***Computed Value***
Hydraulic Gradient	$I = \nabla H / L$	0.083
Shape Factor	$R_f = A / L^2$	0.24
Extent Index	$E = 2(A/\pi)^{0.5} / L$	0.55
Catchment Area Factor	$\propto = 0.2821 * U / A^{0.5}$	1.37

Stream flow is the result of interactions between many hydrologic events, such as precipitation, Evapotranspiration, infiltration, and ground water recharge, with anthropogenic influences, such as land use change and irrigation activities. The upper part of Hare watershed is dissected into two main valleys with the 'Gina stream' in the eastern part and the 'Harere stream' in the western part. The two streams join in the lower valley and form the Hare River. Each of the streams has a relative length of 15.5 km before they join. After they merge at the lower middle part of the watershed, the Hare begins with a length of 13.5 km and results in a length of 29.0 km. In addition, small intermittent tributaries drain into the Hare-River. A gauging site is located at the downstream part of that gauges 85% of the watershed. Moreover, a new automatic radar gauging is established on Gin River in the upper part of the watershed.

(a) (b)

Figure 2. 3 Location of (a) old gauging station at the downstream and (b) a new automatic radar gauging station established at Gina stream

Climate

The climate pattern of Ethiopia is mainly determined by the alternations of the inner tropical convergence zone and the influence of the Indian Monsoon throughout the year. Two major air streams cause dry and rainy seasons: from late June to early September, when the ITCZ is northernmost, the equator dominant air stream direction is south-east in southern Ethiopia and south-west in central to northern Ethiopia. These warm and moist winds are the result of high evaporation and water vapor saturation of the air mass both above the Indian Ocean and the Atlantic Ocean and Congo Basin, respectively. In most parts of the country, annual precipitation follows a bimodal distribution and the annual pattern is commonly distinguished as: main rainy season (*Kirempt*) from June to September; dry season from October to February (*Bega*); and small rainy season from March to May (*Belg*) (Legesse et al., 2003; Thiemann, 2006).

Ethiopians since antiquity have broadly divided their climate into five zones based on elevation. Each zone has its own pattern rainfall pattern and agricultural production system. In general, the highland zones (*Dega* and *Wiena Dega* zones) contain most of the agricultural areas, while the semi-arid and arid lowlands zones (*Kolla* and *Behera*) are dominated by livestock in agro-pastoral and pastoral production systems. Table 2.3 presents the agro-climatic zones the country.

Table 2.3 Agro-climatic zones of Ethiopia

Characteristics	*Agro-climatic zone*				
	Hyper-arid (*Bereha*)	Semi-arid (*Kolla*)	Sub-humid (*Woyna Dega*)	Humid (*Dega*)	Alpine (*wurch*)
Altitude (m)	< 800	800-1500	1500-2300	2300-3000	> 3000
Temperature (^{o}c)	>20	18-20	16-18	13-16	<13
Rainfall (mm)	<200	200-800	800-1200	1200-2200	>2200
Dominant crops	Sorghum, maize	Sorghum, maize	Teff, maize, wheat	Barely, wheat	Barely

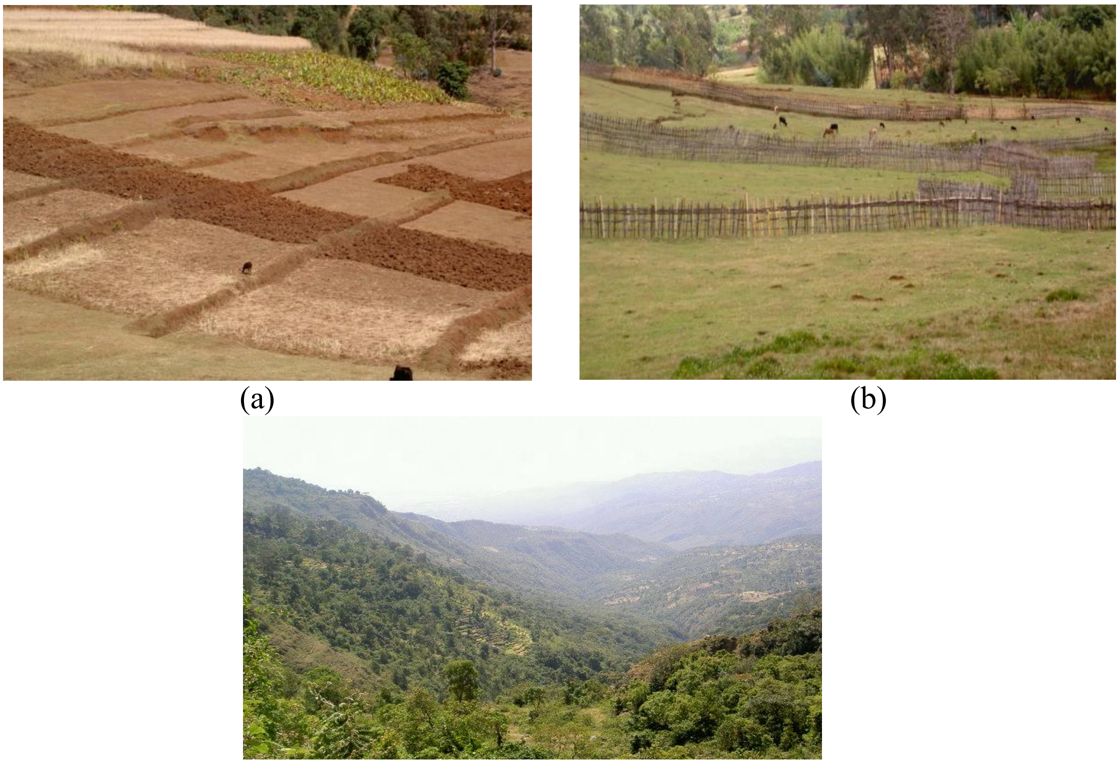
Accordingly, precipitation is generally dependant on altitude in the Lake Abaya-Chamo Basin (Seleshi, 2001; Thiemann, 2006). More specifically, Thiemann and Foerch (2005) identified the dependence of precipitation on altitude is more pronounced in the rainy season than in the dry season and concluded that significant correlation between altitude and precipitation exist during the rainy season (February to September), but no or only weak could be detected in the dry season (October to January). Overall, they high lightened that relatively higher precipitation is observed in the mountainous region as compared to the Rift valley.

The climate of the Hare watershed ranges from tropical to alpine due to its great difference in altitude and topographical elevation. The average annual temperature are 23°C and 14°C, and mean annual rainfall are 750 mm and 1300 mm at the lowland and highland respectively. Generally, about 55.56% is *Dega (Humid*), 22.84% is *Woyna Dega (*Sub-humid*)*, 11.73% is *Wurch (Alpine)* and 9.25% is *Kola* (Sub-arid). The lower watershed area is characterized by dry *Kola* while the middle part of the watershed is characterized by moist *woyna-dega* and much of the area in the northern part is dominated by *Dega* and the tip is *Wurch.* The main and small rainy seasons at Hare watershed occur from April-May and September and October respectively. The spatial rainfall distribution at Hare watershed indicates that major increase of rainfall takes place with an increase in elevation from 1180 m up to 3,480 m above sea level (a.s.l.).

2.4 Land Use and Farming Systems

Understanding farming systems has been recognized as a basis for determining research and development strategies and priorities, so that technologies are developed and development is planned that will be relevant to the farmers' needs and dynamic circumstances. A farming system and how people manage their natural resources are determined by: their principal means of livelihood, biophysical conditions, the degree of the integration between crop and livestock production system, the level of the technology in crop production, types of crops grown, species of animal raised, custom and culture of the people, settlement patterns, values and beliefs systems, social status and stratification, political system etc. These factors may have positive or negative impacts on the natural resources that need close examination based on historic events (Tesfaye, 2003).

The development of agriculture in Ethiopia has followed different patterns. The present landscape of Ethiopia is the result of farming system developed in different parts of the country. The agricultural system of the country can be broadly classified into four types: the seed-farming complex, the enset-planting complex, shifting cultivation and the pastoral complex. The farming system at Hare watershed is an enset-based mixed cropping complex. Farmers grow crops including maize, cotton, sweet potato, and banana (in the lowlands) and barley, wheat, enset, local and sweet potato, peas, beans, onion and apple in the middle and upper sub-watershed.



(a) (b)

(c)

Figure 2. 4 Land use and farming systems at Hare watershed (a) agricultural, (b)grazing and (c) Mixed forest

Farmers in Hare watershed have unique traditional hand digging tool called ‘tsoile’ to cultivate their lands that makes the area among the few exceptions as opposed to central and north highlands of the country where oxen-plough is dominated. The reason behind is the slope of the area and the smaller patches of farming lands doesn’t favour to use ox-plough in the watershed. The *enset (ensete ventricosum*), a banana-like perennial crop used for human food, fiber, animal forage and handicraft products, plays a crucial role for household subsistence. It is cultivated around every farmer’s house and most common staple food in and around the watershed that highly supplements the cereals and tuber crops. The whole processing of the enset crop is left to women. Like everywhere in the highlands of Ethiopia, livestock is an integral part of farming system and farmers have adopted controlled grazing practices in most part of the watershed. However, as compared to nearby watersheds, the numbers of livestock are limited in Hare watershed (Chencha Woreda Report, 2004).

2.5 Water Resources Use and Management

Ethiopia is endowed with a substantial amount of water resources. The surface and ground water resources potential are impressive about 123 and 2.6 BM^3, respectively. The country has 12 river basins which form four major drainage systems. One of these drainage systems is the Rift Valley Basin (Awash, Denakil, Omo-Gidbe and Central Lake) that covers 28 % of the total potential of the country. Based on the total irrigated area, annual agricultural water use is estimated to be in the order of 5.2 BM^3, while domestic and individual water withdrawals are estimated to be about 0.33 and 0.02 BM^3 respectively (FAO, 2002).

Table 2.1 presents irrigation development in the country on regional basis. It illustrates that a considerable irrigated land in the country (about 56%) is served by traditional schemes.

Table 2.4 Irrigation development in Ethiopia (Source: Tilahun and Paulos, 2004)

Region	***Current Irrigation activities***			***Irrigable potential (ha)***	***Total developed (ha)***	***Percent (%)***
	Traditional	**Modern**				
		Small	**Medium/ large**			
Oromia	56,807	17,690	31,981	1,350,000	106,478	7.9
Amhara	64,035	5,752	-	500,000	69,787	14
SNNP	2,000	11,577	6,076	700,000	19,653	2.8
Tigray	2,607	10,000	-	300,000	12,607	4.2
Afar	2,440	-	21,000	163,554	23,440	14.3
Ben Shangul	400	200	-	121,177	600	0.5
Gamblea	46	70	-	600,000	116	0.02
Somali	8,200	1,800	2,000	500,000	12,000	2.4
Harari	812	125	-	19,200	937	4.9
Dire Dawa	640	860	-	2,000	1,500	75
Addis Ababa	352	-	-	526	352	66.9
	138,339	**48,074**	**61,057**	**4,256,457**	**247,470**	**5.8**

In previous days, it is quite evident that irrigation development in Ethiopia did not attempt to involve the farming population. Modern irrigation by and large bypassed farmers, and the technology involved, and the operation and management of this technology was entrusted to a small technical and managerial elite working for medium/large-scale interests in the past and later for state enterprises. On the other hand, there is a long tradition among farmers of water management for small-scale agricultural use.

The majority of existing traditional irrigation schemes are micro-level in size, serving a small group of households. But there are some schemes that serve a large number of beneficiaries. Many of these schemes are based on stream diversion, but some may be dependent on perennial springs. Irrigation in Hare watershed can be considered as a combination of both modern and traditional irrigation systems. Though the River is small, it is extensively used by downstream farmers to irrigate a command area of 2224 hectares that comprises of three different features: a modern diversion with traditional delivery system to Kola Shara Kebele, a fully traditional right side intake to Chano Dorga Kebele and a modern diversion weir at water delivery structure to Chano Chalba and Chano Mile (Belete, 2007).

Moreover, there are also tradition ways of irrigation water use in the upper part of the watershed where hand-dug wells are used as sources of irrigation water. Since traditional irrigation is usually a complement to rain-fed agriculture, the crops grown are often horticultural crops and fruit trees. Farmers have a keen awareness of the benefits of irrigation and are willing to invest their labour in the construction two new modern irrigation schemes in the upper and middle reach of the watershed with a financial support from world vision.

(a) (b)

Figure 2. 5Water resource utilization through diversions at the downstream of Hare watershed

Establishing the value of irrigation water is relevant for smallholder irrigation development more in general, especially in contexts where reliability and adequacy of water supply is low. It becomes necessary to put the available resource more effectively that aims efficient irrigation water management to optimize crop yield. Moreover, the ever-increasing water demand throughout the watershed compared with the depleting water resources warrants refined water use practices in irrigated agriculture to attain improved socioeconomic benefits.

2.6 Population and Socio-Economic Conditions

According to the 2007 census, the population of Ethiopia is 73.9 million (CIA, 2009 estimates is 85.2 million) and it the second populous country in Africa. The population of the country grew at an average annual rate of 2.6 percent between 1994 and 2007—a decrease of 0.2% from the annual growth rate during the previous period (1984-1994) (CSA, 2008). The UN Population Division (2008) predicts the population will reach 107.9 million by 2020, and 173.8 million by 2050. This burgeoning population places enormous strains on Ethiopia's natural resources; the fact that such a large percentage of the population is young means the pressure on the environment will only increase over the next several decades.

Seleshi (2001) indicated that the socio-economic situations of the Abaya-Chamo Basin is variable ranging between nomadic life-to peasants producing cash crops –to the trading or white collar in the urban area. However, the community at the Hare watershed has their own distinct socio-economic situation. The main ethnic groups in the study area are Dorze, Gamo and Ocholo people. The area has high population density, 323 people per km² (Chencha Woreda Report, 2004) as compared to 134 people per km² the Southern Nations, Nationalities and Peoples Region (one of the 12 regional states of the country), which in turn is higher than the nation population density 70 people per km² (CSA, 2008). The indigenous knowledge of a community in the region is derived from the local people's farming experience. It entails many insights, perceptions, and intuitions, relating to local environment. For instance, Tesfaye (2003) pointed out that land management in Konso is the result of a continuous adaptation of the environment to meet the needs on the community. The people have developed a culture of hard work and a knowledge-intensive system of production.

This same analysis holds true for the community living in Hare watershed. They primarily belong to the Dorze community (with other communities) that live mainly in the Chencha woreda and its surroundings. They are weaving and a farming community from which men often migrate to sell their goods in more favourable urban markets. Thus, the production of *'shemma'* (traditional clothing) and other traditional textiles in home based industries is dominated by the people who currently live in the capital and other towns originally come from mainly Chencha Woreda where Hare watershed is situated. The division of labour by sex is more rigid in the weaving community than the fully farming community. Most of the agricultural tasks are shared by men and women, but weaving is exclusively a male activity. The housing system the community is also unique and beehive fashioned made from bamboo, and usually they are much taller in size than others of this style.

CHAPTER 3

Land Use and Land Cover Changes

3.1 Land Use and Land Cover: Definitions and Concepts

The International Geosphere-Biosphere Program, The International Human Dimension Program and the Land Use and Land Cover Change project have referred to 'land use and land cover change' as follows (IGBP-IHDP, 1999). ***Land cover*** refers to the physical and biophysical characteristics or state of Earth's surface and immediate, captured in the distribution of vegetation, water, desert, ice and other physical features of the land, including those created solely by human activities e.g., settlements. ***Land use*** refers to the intended use or management of the land cover type by human beings. Thus, land use involves both the manner in which the biophysical attributes of land are manipulated and intent underlining that manipulation (the purpose for which the land is used e.g., agriculture, grazing, etc), which are more subtle changes that affect the character of the land cover without changing its overall classification. Definition of land use in this way establishes a direct link between land cover and the actions of people in their environment (FAO, 1998a).

Land Use and Land Cover Changes (LUCC) is the shift in intent and/or management constitute land use and land cover. LUCC can be classified into land use and land cover conversions, and land use and land cover modification. Conversion refers to change from one cover or use type to another, as is the case in agricultural expansion, deforestation, or change in urban extent. Land use and land cover modification, on the other hand, involves the maintenance of broad cover or use type in the face of change in its attributes. Both conversion and modifications of land use and land cover have important environmental consequences through their impacts on soil and water, biodiversity, and microclimate, hence, contribute to watershed degradation (Stolbovoi, 2002; Lambin et al., 2003).

LUCC is always caused by multiple interacting factors originating from different levels of organization of the coupled human environment systems. It is the result of complex interactions between several biophysical and socio-economic conditions which may occur at various temporal and spatial scales. The mix of driving forces of LUCC varies in time and space, according to specific human-environment conditions. Understanding the underlying LUCC drivers is an important input for planning and decision making (Xiuwan, 2002).

Lambin, et al., (2003) described the fundamental causes of LUCC as: (1) resource scarcity leading to an increase in the pressure of production on resources *(population of resource users, labour availability, quantity of resources, and sensitivity of resources);* (2) changing opportunities created by markets *(market prices, production costs, transportation costs, and technology);* (3) outside policy intervention *(subsidies, taxes, property rights, infrastructure, and governance)*; (4) loss of adaptive capacity and increased vulnerability*(exposure to external perturbations, sensitivity, and coping capacity)*, and (5) changes in social organization, in resource access, and in attitudes*(resource access, income distribution, household features, and urban-rural interactions).* As a result, information on LUCC has an important role to play at local and regional planning and management natural resources (Ramachandra and Kumar, 2004).

Quite often the study of LUCC is necessitated by the need to know, in quantitative terms, the nature, the extent and the rate at which these changes advance and the problems or impacts they cause. Furthermore, some studies tried to comprehend the effect of changes in upstream land use and land cover, resulting alterations in the movement of water and water availability at the downstream. Increased consciousness of these impacts enhanced their estimating, forecasting and modelling at the regional scales. However, quantifying impacts of LUCC and managements practices at a watershed scale is still complex because of the inherent variability and complex interactions among the different factors. Thus, in order to provide foundations for effective management of natural resources, an understanding must be built on the variability in time and space of the resources and role of human cultures and institutions in bringing those variations (Thomas, 2001; Awasthi et al., 2002).

Comprehensive knowledge of LUCC is useful for reconstructing past land use and land cover changes and for predicting future changes, and thus may help in elaborating sustainable management practices aimed at preserving essential landscape functions (Hietel et al. 2004). The primary drivers of LUCC and their interrelationship with the hydrological regimes has to be identified to develop projections of future land use and management decision outcomes under a range of economic, environmental, and social scenarios.

Currently, improved understanding of processes of LUCC has led to a shift from a view condemning human impact on the environment as leading mostly to a deterioration of earth system processes to emphasis on the potential for effective utilization of resources and ecological restoration through watershed management. This change reflects an evolution of the research questions, methods, and scientific paradigm (Victor and Ausubel, 2000). As a result, general statements about impacts of LUCC and land–water interactions need to be continuously questioned to determine whether they represent the best available information and whose interests they support in decision-making processes (FAO, 2002; Bewket and Sterk, 2004).

3.2 Land Use and Land Cover Change Studies in Ethiopia

Much of our understanding of LUCC has built up from individual case studies, using both remote sensing and ground-based data, and we will continue to rely on case studies as a means to gain required knowledge. Studies that have been carried out at different parts of Ethiopia indicated that croplands have expanded at the expense of natural vegetation, including forests and shrublands; for instance Solomon, 1994 (West Ethiopia); Gete and Hurni 2001(North-Western Ethiopia); Belay 2002 (North Ethiopia); Girmay 2003 (North-Eastern Ethiopia); Gregor et al., 2004 (South Ethiopia); Selamyihun 2004; Bewket, 2004 (North Ethiopia); Mekuria, 2005 (South-Western Ethiopia); and Solomon, 2005 (North Ethiopia). Shibru *et al.* (2003) and Selamyihun (2004,) reported the effect of LUCC in causing major gullies and quantified the rate expansion and their effects on the livelihoods of people in eastern and central highlands of Ethiopia.

Recently, Hadgu (2008) identified that natural vegetation depletion and agricultural land expansion and intensification over a period of 41 years in Tigray, northern Ethiopia. He concluded that population pressure was an important driver for expansion and intensification of agricultural land in recent periods. Similarly, Amsalu et al., (2007) indicated that an increase in agricultural land at the expense of natural vegetation in central highlands. On the other hand, Bewket and Sterk, (2005) pointed out an increase in woodland area in recent years due to afforestation efforts in Blue Nile basin, North Ethiopia. .

In many parts of the highlands of Ethiopia, agriculture has gradually expanded from gently sloping land into the steeper slopes of the neighbouring mountains. According to many literatures, population that has been steadily increased at a growth rate of 2 to 3% per year during the past five decades is the major cause of this expansion. Projected estimates show that the population of the country will be double in 40 years time (UN Population Division, 2008). In some areas, expansions of cultivation, commonly into steeper slopes and marginal areas, may have been done without appropriate soil and water conservation measures. Despite this increase, the agricultural productivity is lagging behind the population growth rate. On the other hand, the per capita land holding is also expected to decline from an average of 1.76 ha in 1985 to 0.66 ha in the year 2015 (IUCN, 1990).

The impact of population growth on the environment and poverty is not simple and one directional (Bewket, 2004). Basically, the complex relationship between human development and the environment is what causes land degradation, in which the use and management of the natural resources is a central issue. In the case of Ethiopia, views with regard to the relationship between population growth and agricultural change can be seen from two directions. The well known Malthusian and the Boserupian theories of agricultural change that have been debated over the years and across disciplines have also been discussed from Ethiopian perspectives (Pender et al., 2001; Mekuria, 2005; Solomon, 2005). These two schools of agricultural change theories see population growth as a central cause of the degradation of the environment (Malthusian perspective) and a prerequisite for the maintenance of the environment (Boserupian perspective). Contemporary outlooks on the population-environment connections are quite different. However, empirical evidence shows that population growth is one of the cardinal causes of environmental degradation in developing countries (Mekuria, 2005).

For instance, population pressure has been found to have negative effect on scrublands, Riverine vegetation and forests in Kalu district (Kebrom and Hedlund, 2000), Riverine trees in Chemoga watershed (Bewket, 2004), and natural forest cover in Dembecha Woreda north-western Ethiopia (Gete and Hurni 2001). Similarly, Pender et al., (2001) found that population growth has contributed significantly to land degradation, poverty and food insecurity in the northern Ethiopian highlands. Gregor et al., 2004 underlined that the primary cause for affecting vegetation cover in the Abaya-Chamo basin is the fast population growth and resulting pressure on the land use ecosystems by expansion of settlements, clear-cutting, expansion of tillage areas and intensification of pasture. Even in earlier study Hurni, (1990) indicated that population pressure in Ethiopia is inducing, the clearing of forests for agriculture and other purposes. Contrary to this, case studies at Sebat Bet Guraghe area, central Ethiopia (Muluneh, 2003) and Konso, southern Ethiopia (Kahssay, 2003) have highlighted a more positive impact of a high density of population mainly due to indigenous knowledge of the people for natural resources conservation. Similarly, Tiffen et al. (1994) pointed out a situation where population increase and intensification of agriculture resulted in less erosion in the Machakos District of Kenya.

However, most of the empirical evidences indicated that land use and land cover changes and socioeconomic dynamics have a strong relationship; as population increases the need for cultivated land, grazing land, fuel wood; settlement areas also increase to meet the growing demand for food and energy, and livestock population. Thus, population pressure, lack of awareness and weak management are considered as the major causes for the deforestation and degradation of natural resources in Ethiopia.

3.3 Data and Methodology

3.3.1 Data Acquisition and Pre-Processing

LUCC experienced in a watershed can be observed from processed aerial photographs and satellite images. Since remote sensed data from the earth orbit can be obtained repeatedly over the same area, they have been very useful to monitor and analyze LUCC in various regions of the earth. A step-by-step evaluation of the images allows one to better understand the cause and effect relationship regarding the LUCC over time. Empirical evidence of LUCC delivered by repeated aerial photography and/or satellite images can greatly contribute to planning and management of available resources, especially in the developing countries where other kinds of background data are often lacking (Tekle and Redlund, 2000). Subsequently, in this research spatial databases were developed using aerial photographs, satellite image from LandSat Enhanced Thematic Mapper and intensive land use mapping using Geographical Positioning System (GPS). The establishment of the databases involved:

1) Acquisition of a semi-processed satellite image (2004) and Black and white aerial photographs (1967 and 1975) with scale of 1:50,000, topographic maps (1:50,000) from Ethiopian Mapping Authority.
2) Identification of Ground Control Points (GCP's) before interpretation of the aerial photographs and satellite images commences. At each GCP location, GPS measurements were taken during a field work in 2005 so as to verify and confirm the information gathered through remote sensing.
3) Scanning of the aerial photographs at 600 dots per inche (dpi) resolution and geo-referencing the 1967 aerial photo mosaics to the Universal Transverse Mercator (UTM) system using 1:50,000 topographic map
4) Geo-referencing (geo-rectifying) the 1975 aerial photos and satellite image using the same topographic maps the imagery was remapped and projected to UTM ground coordinates.
5) Producing land use and land cover maps of 1967, 1975 and 2004, and organization of the maps for further processing.

3.3.2 LUCC Detection and Quantification Procedures

LUCC detection is the process of identifying differences in the state of an object or phenomenon by observing it at different times. Essentially, LUCC detection involves the ability to quantify temporal effects using multi-temporal data sets. Macleod and Congalton (1998) list four aspects of change detection which are important when monitoring natural resources: (1) Detecting that changes have occurred; (2) Identifying the nature of the change; (3) Measuring the aerial extent of the change and (4) Assessing the spatial pattern of the change. Efficiency of the techniques depends on several factors such as classification schemes, spatial and spectral resolution of remote sensing data, ground reference data and also an effective implementation of the result.

The generic approach of the LUCC is based on post-classification comparison method, which is commonly employed in land cover change detection studies. This method was found to be the most suitable for detecting LUCC (Larsson 2002; Liu and Zhou 2004). In this technique, two types of images from different dates are independently classified. The use of independently produced classifications has the advantage of compensating for varied atmospheric and phonological conditions between dates, or even the use of different sensors between dates, because each classification is independently produced and mapped. Thus, this study is based on post classification comparison of independently developed and classified land cover maps of the 1967 & 1975 aerial photographs and the 2004 satellite image with a verification of GCPs.

The flow chart in Figure 3.1 shows the procedures followed during the LUCC detection, quantification and the input resources used.

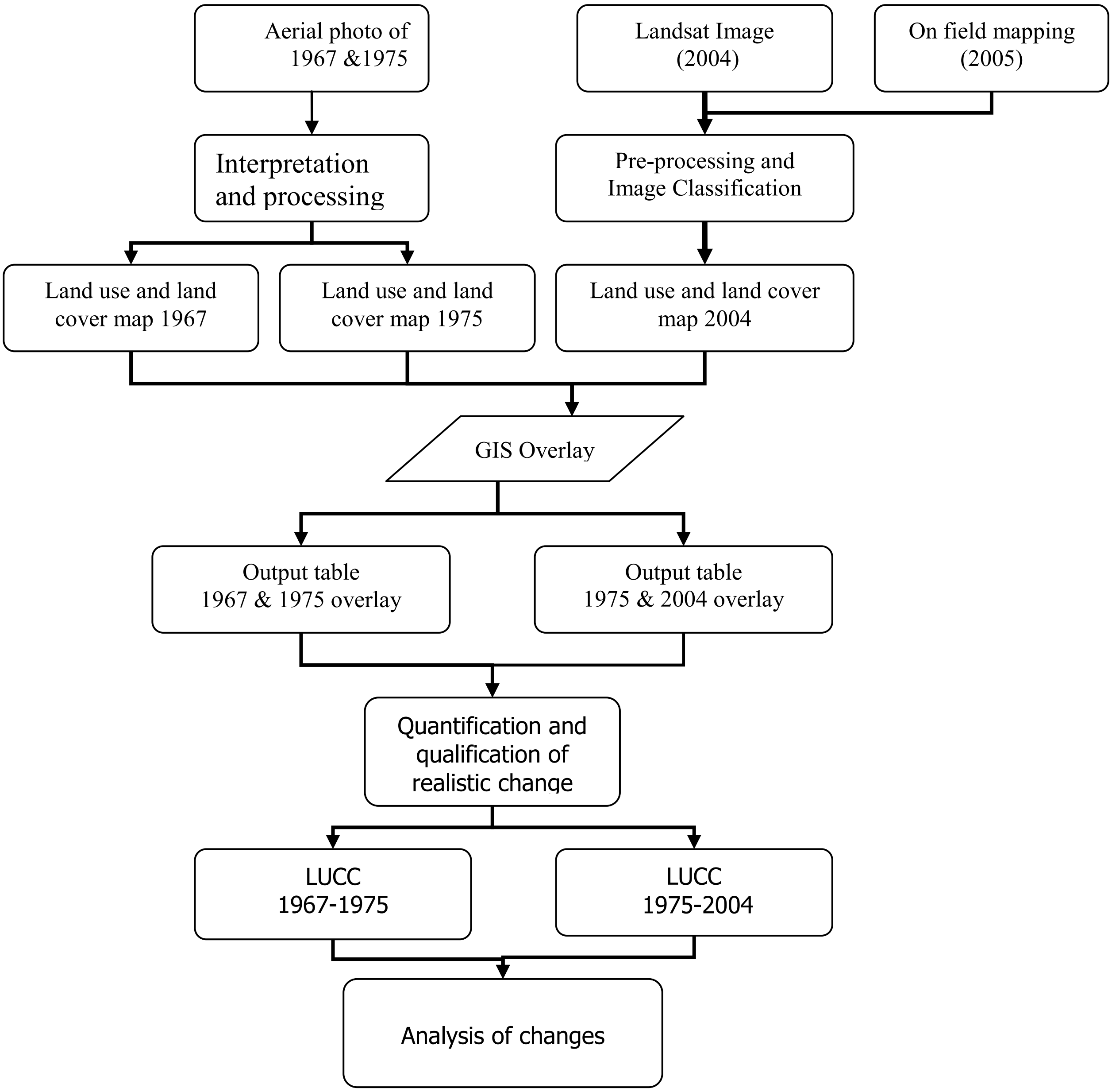


Figure 3.1 A Summary of land cover change detection and quantification

With the two types of remotely sensed data, photographs and imagery, there is a danger that differences between time periods may result from differences in data collection rather than from actual changes taking place on the ground. This danger was minimized in two ways. First, five broad land use and land cover categories (Table 3.1) were used, which could be clearly distinguished on both the photographs and the imagery. Second, an intensive ground-truth data was conducted through the period February to May 2005. A total of 126 GCPs were identified and used for accuracy assessment from each land use and land cover classes: farmland and settlement (61), forest (16), woodland and shrubs (21), grassland (17), and Riverine trees and bamboo (11). Patches different land use and land cover were mapped out for the whole watershed by taking GPS readings at representative sites of each land use and land cover class. Moreover, for historical ground-truth of the 1975 aerial photo, farmers were interviewed in each sub-watershed to supplement the remote sensed data.

Table 3.1 Land use and land cover categories identified at the Hare Watershed (Modified after Bewket, 2004)

Cover type	***Classification rule***
Farmland and settlement	Areas used for crop cultivation, both annuals and perennials, and the scattered rural settlement that are closely associated with the cultivated fields. It includes areas currently under crop, fallow and land under preparation. The two land cover types were combined due to the reason that it was difficult to identify the dispersed rural settlements s as a separate land cover type and cultivated lands exist around homesteads.
Forest	Land covered with dense trees and undergrowth that formed nearly closed canopies.
Woodlands and Shrub lands	Areas with scattered trees mixed with short bushes, grasses and open areas
Grasslands or Pasture lands	Grassy areas used for communal grazing, as well as bare lands that have very little grass or no grass cover (exposed rocks). It also includes other small seized plant species.
Riverine trees/Bamboo	Liner areas of Bamboo, trees and shrubs along the stream courses

The majority of classification projects today make use of digital classification procedures, guided by human interpretation. Thus, both the visual interpretation and computer-assisted interpretation were used to classify the images. The aerial photographs were interpreted using three main criteria, grey scale, textural and proximity factors. Grey scale relates to colour variations. In the upland areas dark grey areas with a smooth texture that tended to be located far from cultivated areas were classified as forest. Lighter grey areas with a rough texture that tended to be located close to cultivated areas were classified as woodlands and shrubs. Light grey areas with a smooth texture that tended to be situated near to settlements were classified as farm lands. Rounded patches that are located at the top of hill slope having light textures were classified as grassland. Very deep dark grey areas following the stream net work were classified as Riverine trees and bamboo land use and land cover classes.

IDRISI 32 Release 2 (Eastman, JR 2001), which is a combined GIS and image processing system that offers advanced capabilities in both areas, was utilized to process and classify the 2004 satellite image. Supervised classification based on the maximum likelihood classifier algorithm of the tool was used for the classification purpose. The false colour composite was used for the visual examination and interpretation. The training signatures to perform this classification were based on the 126 training sites during the field study in 2005. During the interpretation of the images, in areas where there was no distinct spectral signature within the land cover types as a result of mixed pixels the ground truth data was used and on screen digitizing technique applied to demarcate the classes.

3.4 Results and Discussion

Following the step-by-step detection and quantification procedures on the aerial photographs and satellite image, three land use and land cover maps of 1967, 1975 and 2004 were produced. Subsequently, spatial analyses were carried out to describe structural land use and land cover patterns, overall land use changes over time, measure the rate of change, and relate spatial and structural patterns of LUCC at watershed and sub-watershed levels. Generally, farmlands and settlements, and grasslands are situated at the upper part of the watershed and forest and woodlands at the lower and middle reach of the watershed.

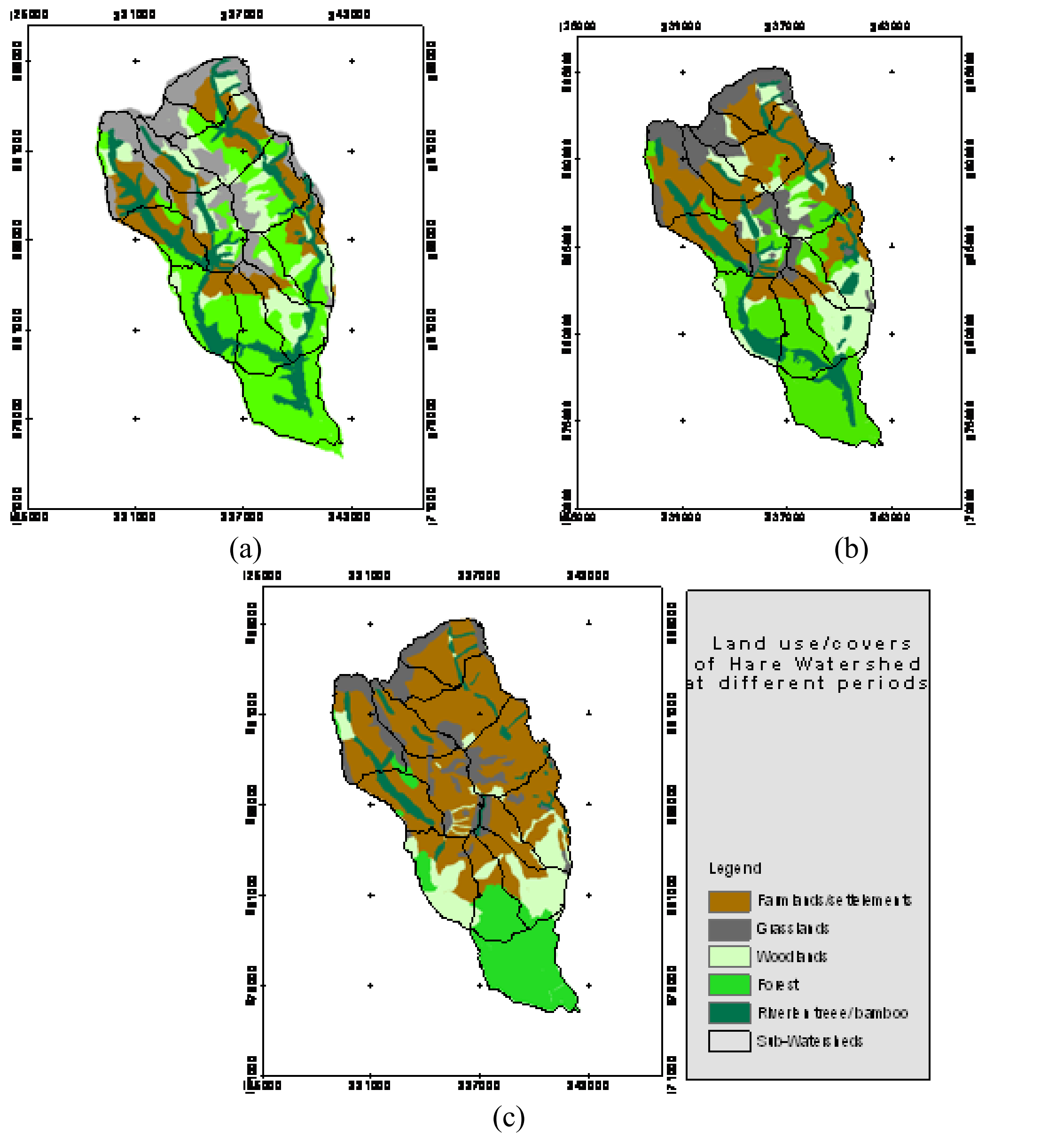


Figure 3.2 Land cover map of 1967 (a), 1975 (b) and 2004 (c) at Hare watershed

3.4.1 LUCC at Watershed Level

The overall land use /cover changes at watershed level are summarized in Table 3.2. The LUCC has an identical trend during the two periods (1967-1975 and 1975-2004). It can be depicted from Figure 5.1 and Table 5.1 that in 1967 forest was the major land use (34.4%) followed by grasslands (19.6 %), and farmland and settlements class was having only a share of 16.5%. These land use types have common physical and geographical inter-connections, as an area increase in one type of land use category will be associated with an area decrease in another land use category. The changes happened in the areas with soil fertile enough to grow crops (normally along highland valleys), less steep slopes, and close to settlements. The upper part of the watershed and the border zone in between the uplands and lowland were the most affected areas.

Table 3.2 Summary Land use and land cover types and changes from1967-2004 at Hare watershed

Land use and land cover type	Land use and land covers						LUCC			
	1967		1975		2004		(1967-1975)		1975-2004)	
	Area		Area		Area		%	Rate (ha/yr)	%	Rate (ha/yr)
	(ha)	(%)	(ha)	(%)	(ha)	(%)				
Farmland and settlement	2755.8	16.5	4728.3	28.3	8699.0	52.0	+71.6	+ 246.6	84.0	+136.9
Forest	5757.0	34.4	4757.7	28.4	2715.5	16.2	-17.4	- 124.9	-42.9	-70.4
Woodlands/ Shrub lands	2113.8	12.6	2304.6	13.8	1970.8	11.8	+ 9.0	+ 23.9	-14.5	-11.5
Grasslands/ Pasture lands	3278.3	19.6	2842.8	17.0	2306.5	13.8	-13.3	- 54.4	-18.9	-30.1
Riverine trees/ Bamboo	2827.7	16.9	2099.2	12.5	1040.8	6.2	-25.8	- 91.1	-50.4	-36.5
Total	**16732.6**	**100.0**	**16732**	**100.0**	**16732**	**100.0**				

It can be observed in the above table that dense forest was changed to farmlands and settlements and, some forests were altered to woodlands in both the first and second periods. Moreover, it is remarkable that the rate of change to farmlands/ settlement was very high in the first period (+246.6 ha/year) than that the second period (+136.9 ha/year). However, the most significant period of expansion of farmlands and settlements (84%) and reduction of other land uses was in the second period (1975- 2004), during which time almost 41% of the vegetation at the beginning of that period was lost to farmlands and reduced to 22.4%.

Research results from previous studies reflect the same fact. For instance, Mekuria, (2005) reports 75% of at Shomba catchment, in the south western part of Ethiopia, was converted to farmlands and settlements from other land uses between the years 1967 to 2001. Gete and Hurni (2001) identified that that 99 % of the forest covers was converted to agricultural land at Dembecha area in the northern part of the country between 1957 and 1995. They also observed that cultivation expanded to marginal areas as steep as > 30 % slope. Bewket (2004) reports agricultural conversion of 79 % of the Riverine forests of the Chemoga watershed within the Blue Nile basin in about 40years (1957-1998). Figure 3.3 below clearly illustrates the percentage of cover of the land use and land covers and patterns of the changes took place during the study periods.

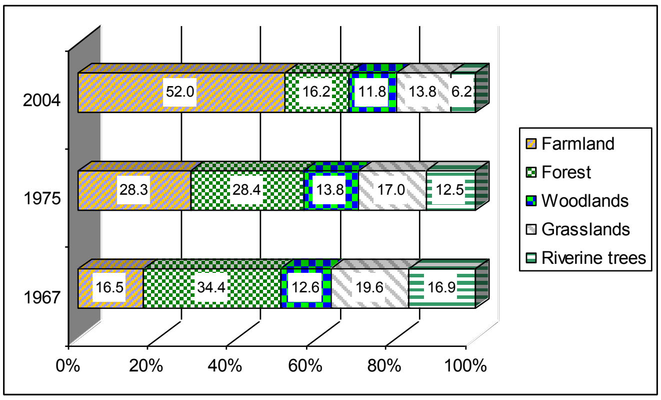


Figure 3.3 Percentage changes of land use and land cover classes

The percentage of decrease of grassland and pasture are higher in the second period (18.9%) than the first period (13.3%) while the rate of change was higher in the first period (-54.4 ha/year) than the second period (-30.1 ha/year). On the contrary, wood land and bush lands class slightly increased in the first period (9.0%) with the rate of +23.9 ha/year at the expense of forest lands and decreased by 19.8% at a rate of -11.5 ha/year that changed to farmlands and settlement class.

3.4.2 LUCC at Sub-Watershed Level

As discussed section 4.6.5, SWAT2005 was used to delineate fourteen sub-watersheds. This sub-section discusses the LUCC that occurred at each sub-watershed to get better insights of the land use and land cover conversion at a finer spatial scale. Figures 3.4 illustrate the pattern of land use and land cover changes in each sub- watershed during the two periods.

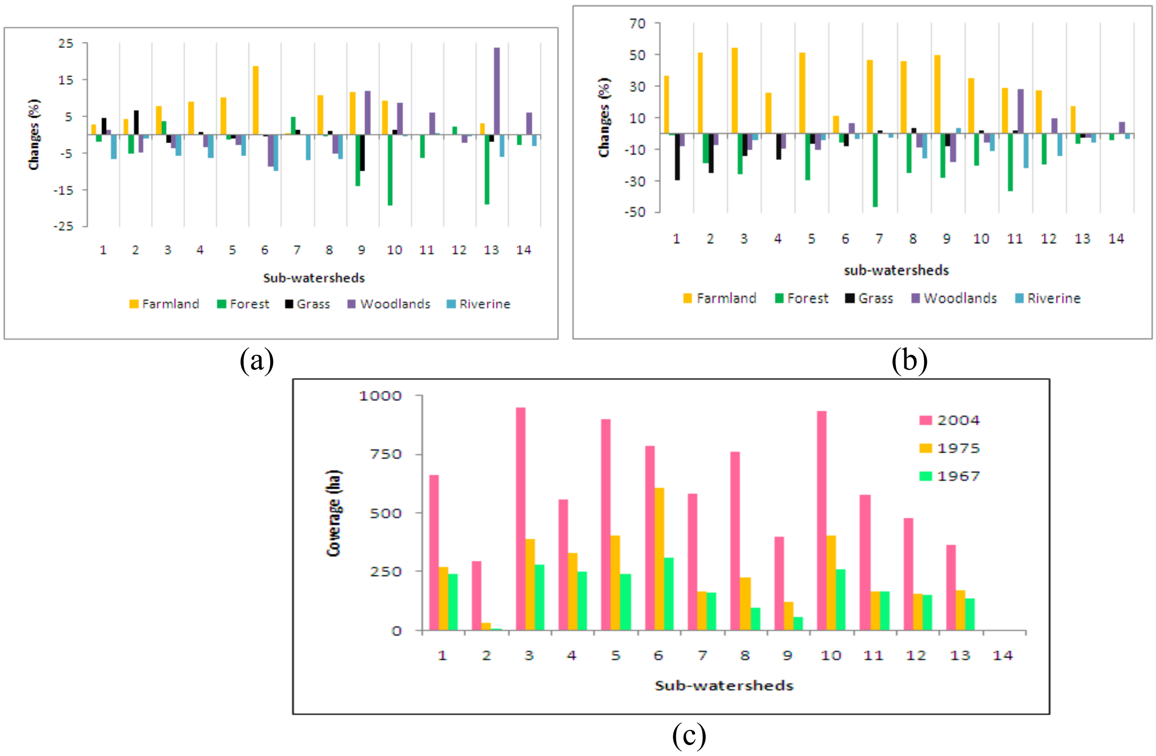


Figure 3.4 LUCC (%) in each sub-watershed for the period of (a) 1967-1975, (b) 1975-2004 and (c) Farmlands and settlements changes

The percentage of increase in farmlands and settlements has almost occurred in all sub-watersheds in the second period with a higher percentage than the first period. Sub-watershed 6 is an exception where higher percentage of LUCC occurred in the first period than the second. In watersheds 9, 10, 11, 13 and 14 there was increases of woodlands during the first period and in sub-watersheds 11, 12 and 14 during the second period when the forest covers were intervene by human for fire wood, house construction and decrease their canopy cover.

The rate of changes was higher during the first period in sub-watersheds 3(13.3 ha/year), 5(19.5 ha/year), 6(35.1 ha/year) and 8(16.3 ha/year) and during the second period in sub-watersheds 3(27.4 ha/year), 5(27.1 ha/year), 7(14.5 ha/year), 8(19.2 ha/year) and 11(13.7 ha/year). During the second period, the rate of conversion of forest to other land use and land covers were high in sub-watershed 11(-17.7 ha/year), 5(-15.8 ha/year), 7(-14.5 ha/year) and 3(-12.9 ha/year). Whereas other land use and land cover conversion is moderate in most sub-watersheds. Generally, LUCC was very high in sub-watersheds 3, 5 and 6 were 906, 941 and 687 hectares of land has been converted from other land uses to farmlands and settlements throughout the study period (1967 to 2004). On the other hand, sub-watershed 14 is more stable due to its location in deep valleys and unfavourable conditions for farming.

3.5 Implications of Land Use and Land Cover Changes

Before 1974 land tenure in Ethiopia consisted of semi-feudal tenant-landlord relation and there is a gradual expansion of cultivation. According to Terefe, (2001) and Tesfaye, (2003) lack of land security during the monarchy period can be considered as one of the major bottlenecks to improve land management and production. The nearby town to Hare watershed, Chencha had been the capital of Gamu Gofa province until those offices were transferred to the more accessible city of Arba Minch. At that time landlords were the one who give lands to tillers. However, according to elders there was high population and better farming system around the Chencha town than other places. This may be the reason for the high rate of LUCC during the period the first period (1967-1975).

When the Provisional Military Administrative Council (Popularly known as the *Derg*) came to power in 1974, the land reforms (Rural Land Proclamation No.31/1975) broke the relationship between the tenants and the landlords and land was designated as state property. Therefore, immediately after the 'land for the tillers' proclamation, there was an expansion of farmlands and settlements all over the country. Here also the high percentage of change during the second period of the study (1975-2004) could be associated to this fact. During this period agricultural expansion was the leading land-use change associated with all cases of deforestation and wood extraction. Moreover, the rate of reduced forest land and less expansion rate in farmlands and settlements could possibly indicate that land occupation of arable areas has reached its limit in the watershed.

As discussed earlier, the upper part and middle reach of the watershed are predominantly affected by the LUCC during the 1975 to 2004 period. There are several reasons why forest is being cleared, as often mentioned by the local farmers and local governments, is population growth in the area that causes an increase in farmland and settlement and uncontrolled use of firewood from the lower part of the watershed. Based on figures published by the Central Statistical Agency in 2005, Chencha district has an estimated population of 127,193. The district has an estimated high population density of 348.5 people per square kilometre (Chencha Woreda Report, 2004) as compared to 134 people per km^2 the Regional average, which in turn is higher than the national average 70 people per km^2 (CSA, 2008). The reduction in vegetation cover at the study area decreases infiltration and increases surface runoff that alters the whole hydrological regime (see Chapter 5).

3.6 Conclusions

The aim of this chapter was to evaluate changes in land use and land cover change at Hare watershed during the past four decades. The study area is found to be under high demographical pressure, with a population growth rate estimated at approximately three percent per year and high population density. The extremely low income of much of the population result in over-exploitation of natural resources in the basin that can seriously affect the sustainable development of the area.

From this study, it can be concluded that Hare watershed had experienced a significant change in land use and land cover over the past four decades. It can be presumed that deforestation and increase in farmland that was manifested by the rapid increase in human population has altered the whole Hare watershed in general and some sub-watershed in particular. It is identified that land use and land cover changes has an identical trend during the two periods (1967-1975 and 1975-2004). Forest and grasslands were changed to farmlands and settlements, woodlands and bush land were altered to grasslands, but at a decreasing rate when compared to the case of forest conversion to farmland and settlements. The possible reasons for the decrease of Riverine trees could be the cultivation practices of perennial crops along the stream network in the upper watershed. Riverine tree land use class was either modified to Bamboo patches or totally converted to other land uses.

However, the predominant change in land use and land cover during the whole period is the increase in farmland and settlement areas, particularly in the upper part of the watershed, and the overall decline in forest, grasslands and woodlands. Meanwhile, sub-watersheds that are close to small towns are highly affected than the other ones. For instance, SWAT2005 was very useful tool in delineating the sub-watersheds that facilitate to identify LUCC at a finer scale and it also helps in running simulations in order to quantify the impacts of land use and land cover changes on streamflow. Though considerable conversion of other land use and land covers to farmlands may not be anticipated due to the reason that land occupation of arable areas has reached its limit in the watershed, modification of farmlands (rain-fed to small scale irrigations) are expected in the near future.

CHAPTER 4

Watershed Hydrological Modeling in the Context of Sustainable Water Resources Management

4.1 Introduction

The term ‘‘watershed hydrology’’ is defined as that branch of hydrology that deals with the integration of hydrologic processes at the watershed scale to determine the watershed response. A watershed is the area of land from which runoff (from rain, snow, and springs) drains to a stream, river, lake, or other body of water. It is a geographical unit in which the hydrological cycle and its components can be analysed (Singh, 1995). According to FAO (1987) the process of developing and implementing a series of actions for the management of natural, agricultural and human resources within a watershed to provide required and appropriate goods and services to society under the precondition that land and water resources are not negatively affected. In fact, the concept of watershed management has internationally gained significant attention following the United Nations Conferences on Environmental and Development in 1992 in Rio de Janeiro.

Förch and Schütt, (2007) emphasized that integrated watershed management incorporates various disciplines, including natural resources management and geography, water resources management and environmental economics, as well as socio-economic and business administration. The efficient and sustainable utilisation of natural resources as a basis for improving livelihoods is only possible as a bottom-up approach, thus, it is a typical focus as well as a concept of classical development co-operation. The same authors highlighted the problems of soil, water and energy resources management and appropriate solutions in Ethiopia, with a special focus on watersheds in the Southern Rift Valley. In this thesis, focus is given to management of water resources that considers socio-economic equity, systems reliability, sustainability and participation of all stakeholders.

Currently, the utilization of natural resources, such as water and land, is closely interlinked with the goals of sustainable and appropriateness. The resources within a defined watershed should be utilized for the benefit of the local population and in harmony with the environment (Förch and Schütt, 2007). Moreover, the International Conference on Water and the Environment (1992) concluded that scarcity and misuse of fresh water pose a serious and growing threat to sustainable development and protection of the environment. Similarly, the World Water Assessment Programme (2003) described the fact that the world faces water crises that has become increasingly clear in recent years. Challenges remain widespread and reflect severe problems in the management of water resources in many parts of the world. As a result, human health and welfare, food security, and the ecosystems on which they depend, are all at risk, unless water and land resources are managed more effectively in the present decade and beyond than they have been in the past. Moreover, these problems will intensify in the future unless effective and concerted actions are taken.

At present, integrated watershed assessment tools for support in land management and hydrologic research are becoming established tools in both basic and applied research. With advances in computational power and the growing availability of spatial data, mathematical models are attractive tools to analyze the functioning of hydrology, operation, social and economic processes, as well as others that can occur in a basin, with the objective of setting and evaluating management alternatives in water resources management. Basically, hydrologic modelling and water resources management studies are intrinsically related to the spatial processes of the hydrologic cycle. Watershed models are fundamental to water resources assessment, development, and management. They are, for example, used to analyze the quantity and quality of streamflow, reservoir system operations, groundwater development and protection, surface water and groundwater conjunctive use, water distribution systems, water use, and a range of water resources management activities (Singh and Woolhiser 2002).

Hydrological models are, by their very nature, abstractions of reality used to simulate, rather than mimic, natural systems. They are seldom, if ever, truly correct and application of models for management is often considered as much an art as it is a science. This does not imply a lack of rigor, but rather a recognition of inherent uncertainties and the need for the modeler to make intelligent choices in the development, use and reporting of models. Normally, a model can reduce highly complex processes to simple output but, on the other, the strength of a model is determined by the relevance, and often extent, of the input data. Subsequently, modeling can provide a powerful tool for watershed management, but can be fairly meaningless if there is an ill defined objective, poor conceptualization of the causative relationships and their uncertainty, or if insufficient attention is paid to essential technical aspects of the modeling process. Failure to address, or at least be acutely aware of, these issues restricts sensible interpretation of results.

Hydrological modelling is a powerful technique of hydrological system investigation for both the research hydrologist and practicing water resources engineers involved in the planning and development of integrated approach for the management of water resources. Moreover, watershed modelling techniques are useful tools for investigating interactions among the various watershed components and hydrologic response analysis to LUCC and river basin management at various spatial scales (Silberstein, 2006; Refsgaard, 2007). Besides, considerable work has been undertaken in understanding and modeling the processes involved in the hydrological cycle, enabling models to have been developed to address a wide spectrum of environmental and water resources problems (Singh and Woolhiser, 2002).

Generally, Hydrological models are tools that integrate our knowledge of hydrologic systems to simulate the real world hydrologic processes. These models comprise a set of mathematical descriptions of portions of the hydrologic cycle (Singh and Woolhiser 2002) and they are based on a set of interrelated equations that try to convert the physical laws, which govern extremely complex natural phenomena, to abstract mathematical forms. Any hydrological model emphasizes some aspects which are considered relevant instead of others considered of secondary importance, and should be sufficiently comprehensible and easy to be used and in the same way sufficiently complex to represent the physical studied problem. Moreover different varieties of models can be used, depending upon the conceived output, the existing database, input variables and required analysis.

4.2 Water Resources Management

Traditionally, the management of natural resources was strongly split into thematic sectors such as agriculture, forestry or water management, and spatially subdivided into administrative units which rarely follow the elements of the natural landscape. The idea to overcome this impractical and inefficient situation in the water sector is actually more than six decades old but had only a dubious record of implementation until recently. In 2002, at the Johannesburg World Summit on Sustainable Development, The Technical Advisory Committee of the Global Water Partnership (WSSD, 2002) defines Integrated Water Resources Management (IWRM) as "a process which promotes the coordinated development and management of water, land and related resources, in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems" and emphasized that water should be managed in a basin-wide context, under the principles of good governance and public participation. Obviously, surface water, groundwater, quantity and quality are all linked in a continuous hydrological cycle and water as a system interacts with other systems.

Accordingly, the overall goal of Water Resources Policy in Ethiopia (MoWR, 2001) is to enhance and promote all national efforts towards the efficient, equitable and optimum utilization of the available Water Resources of Ethiopia for significant socioeconomic development on sustainable basis. The policy emphasis on allocation and apportionment of water based on comprehensive and integrated plans and optimum allocation principles that incorporate efficiency of use, equity of access, and sustainability of the resource.

As a principal motivating and integrating factor in hydrologic response studies, water must be managed in the full understanding of its importance for social and economic development. Besides, the rapid population growth has caused an increase pressure on land and water resources in almost all regions of the world. Due to increased demand of water for different purposes, water resources have become scarce natural resources. Yet, water resources are not being managed in an efficient and sustainable manner. The increased water resources problem requires improved water resources management tools based on sound scientific principles. The tools has to involve, amongst others, an integrated description of the land phase of the hydrological cycle, an integration description of water quantity, quality and ecology, an integration of hydrological, ecological and economical information designed for decision makers at different levels (Abbot and Refsagaard, 1996).

Most of the problems encountered in the water sector today arise from an issue of conflicts of use and water allocation. With the increase of population and dry spell causing water shortages regularly in many areas resulting in allocation issues and conflicting rights over the limited water supply. The attitude "first in time priority in right" may no longer be an equitable approach in resolving such conflicts. In view of the growing scarcity of water resources for irrigation in some basins and the felt need for effective measures to resolve water shortages and improve water use, consideration of an alternative approach based on deficit irrigation principles has been advocated.

In this study, optimal use and management water in the agricultural sector is considered as major part of IWRM and the country's water resources policy that links land and water development, and social and economic development within the study area. It is a concept that attempts to coordinate and balance between human activities in a given watershed and competing demands among water users in a way that optimizes benefits and enhances equity. Moreover, a wide range of issues including: management of supplies through improving water availability in space and time, management of demands through increasing efficiency of water use, balancing competing upstream versus downstream demands and sustainability of agro-ecosystems can be addressed. Practically, for the agricultural sector, IWRM seeks increased water productivity within the constraints imposed by the economic, social and ecological context of a particular region.

The use of hydrological models has therefore been of interest for integrated water resources management. Specifically, in order to properly quantify integrated effects of a changing land use and climate with high spatial and temporal resolution, the models have to fulfill certain criteria: they should be simple enough to work on large scales, with sparse data and future climate scenarios. This is especially important for the application in developing countries. At the same time, the parameterization should be based on a reasonable representation of the dominant watershed processes and be able to reflect changes in watershed characteristics and forcing data. However, the complexity of the hydrological processes seen in many watersheds makes it difficult to predict the spatial and temporal variation of the processes that occur within the watersheds.

4.3 Hydrologic Model Selection

4.3.1 Hydrologic Models

A watershed hydrology model is an assemblage of mathematical descriptions of components of the hydrologic cycle. The model structure and architecture are determined by the objective for which the model is built (Singh and Woolhiser, 2002). Watershed hydrologic models have been developed for many different reasons and therefore have many different forms. However, they are in general designed to meet one of the two primary objectives. One objective of watershed modelling is to gain a better understanding of the hydrologic processes in a watershed and of how changes in the watershed may affect these phenomena. Another objective of watershed modelling is the generation of synthetic sequences of hydrologic data for facility design or for use in forecasting. They are also providing valuable information for studying the potential impacts of changes in land use or climate. The variety of uses and the rapid increase both in scientific understanding and in technical support, from data collection systems and computer technology, have produced an enormous range in levels of sophistication.

Beven, (2001) described that every hydrological model requires two essential components: one to determine how much of the rainfall becomes part of the storm hydrograph (the runoff production component); the other to take account of the distribution that runoff in time, to form the shape of the storm hydrograph (the runoff routing component). Practical experiences suggest that the complexities and nonlinearities of modelling in the flow generation process are much greater than the routing processes. Hydrological models vary in many ways: time step, spatial scale, whether the model simulates single events or on a continuous basis, and how different hydrological components are computed. Singh and Woolhiser (2002) state that watershed models can be classified according to different criteria that may encompass process description, time scale, space scale and technique of solution

Singh (1995) classified hydrologic models based on (1) process description; (2) timescale; (3) space scale; (4) techniques of solution; (5) land use; and (6) model use. Depending upon the way the hydrological processes are described, the models can be also classified as deterministic, stochastic, or mixed. In a deterministic model outcomes are precisely determined through known relationships among states and events, without any room for random variation. In such models, two equal sets of input always yield the same output if run through the model under identical conditions. On the other hand, if a model has at least one component of random character which is not explicit in the model input, but only implicit or 'hidden' it is called stochastic model. If the model components are described by a mix of deterministic and stochastic components, the model is called stochastic-deterministic or hybrid model. A vast majority of the models are deterministic, and virtually no model is fully stochastic. On the basis of process description, the hydrological models can be classified into three main categories: lumped models, semi-distributed models and distributed models (Figure 4.1).

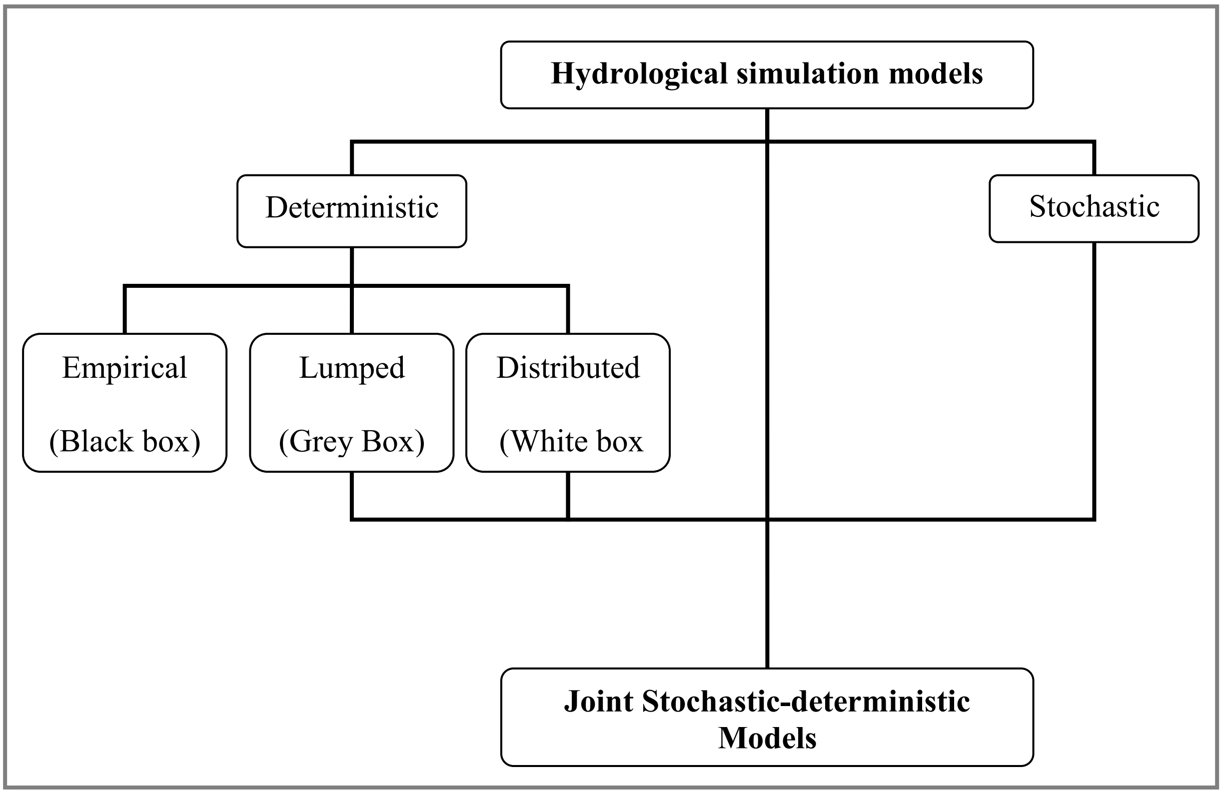


Figure 4.1 Classification of models based on process (Refsgaard, 1996)

Parameters of lumped hydrologic models do not vary spatially within the basin and thus, basin response is evaluated only at the outlet, without explicitly accounting for the response of individual sub-basins. The parameters often do not represent physical features of hydrologic processes and usually involve certain degree of empiricism. The impact of spatial variability of model parameters is evaluated by using certain procedures for calculating effective values for the entire basin. The most commonly employed procedure is an area-weighted average. These models are not usually applicable to event-scale processes while for discharge prediction they can provide just as good simulations as complex physically based models (Beven, 2001). Typical examples of lumped hydrological models include IHACRES (Jakeman et al. 1990), WATBAL (Yates, 1994) and TOPLATS (Famiglietti and Wood, 1994). Most of such models are not capable of representing all hydrologic processes for investigating the impacts of land use and climate change on the hydrological regime.

Distributed models on the other hand fully allow parameters to vary in space at a resolution usually chosen by the user. Distributed modeling approach attempts to incorporate data concerning the spatial distribution of parameter variations together with computational algorithms to evaluate the influence of this distribution on simulated precipitation-runoff behavior. These models generally require large amounts of (often unavailable) data for parameterization in each grid cell. However, the governing physical processes are modeled in detail, and if properly applied, they can provide the highest degree of accuracy. Typical examples of these models include MIKE SHE (Refsgaard and Storm, 1995), CASC2D (Ogden, 1998) and CEQUEAU (Morin, 2002).

Semi-distributed (simplified distributed) models partially allow parameters to vary in space by dividing the basin into a number of smaller sub-basins. The main advantage of these models is that their structure is more physically-based than the structure of lumped models, and that they are less demanding on input data than fully distributed models. SWAT (Arnold, 1993), HEC-HMS (US-ACE, 2001), HSPF (Bicknel et al., 2001), PRMS (Leavesley et al., 1983), DWSM (Borah et al., 2001), TOPMODEL (Beven et al., 1993), HBV (Bergström, 1995), are considered as semi-distributed models.

Furthermore, hydrologic models can be divided into event-driven models, continuous-process models, or models capable of simulating both short-term and continuous events. Event-driven models are designed to simulate individual precipitation-runoff events, are capable of simulating short-term events. Their emphasis is placed on infiltration and surface runoff, their objective is the evaluation of direct runoff. Typically, event models have no provision for moisture recovery between storm events and, therefore, are not suited for the simulation of dry weather flows. On the other hand, a continuous model simulates instead a longer period, predicting watershed response both during and between precipitation events. These models take explicit account of all runoff components, including direct and indirect runoff. They focus on long-term hydrologic abstractions responsible for the rate of moisture recovery during the periods of no precipitation. They are suited for simulation of daily, monthly or seasonal streamflow, usually for long-term runoff-volume forecasting and for estimates of water yield (Singh, 1995).

4.3.2 Guidelines for model selection

The selection of a particular model is a key issue to get satisfactory answers to a given problem. Currently, there are numerous hydrological models simulating the hydrological process at different spatial and temporal scales. Although there are no clear rules for making a choice between models, some simple guidelines can be stated. Starting from the studied physical system, the first step is to define the problem and determine what information is needed and what questions need to be answered. This means that it is necessary to evaluate the required output, the hydrologic processes that need to be modelled, availability of input data. Subsequently the simplest method that can provide the answer to the questions has to be chosen. In particular it's necessary to identify the simplest model that will yield adequate accuracy, bearing in mind that model complexity is not synonymous with the accuracy of the results, that the model has to be characterized by flexibility, by the possibility of making it applicable under various spatial and temporal conditions and that increased accuracy has to be worth the increased effort.

Nowadays, different models are being used to forecast effects of climate and land use change on hydrological process (Bormann and Diekkrüger, 2003; Giertz and Diekkrüger, 2003; Legesse et al., 2003). Recently, hydrological simulation models including: SWAT2005, MIKE-SHE, HSPF, WASIM-ETH, DHSVM, HEC-HMS and others have been developed partly to quantify the influence of change in land use, land cover and management practices on the hydrologic cycle. Moreover, with the development of Geographic Information Systems (GIS) and remote sensing techniques, the hydrological catchments models have been more physically based and distributed to enumerate various interactive hydrological processes considering spatial heterogeneity (Mohan and Shrestha 2000). GIS has the ability to store, retrieve, manipulate, analyze, and display data efficiently according to the user defined specifications. Hence, the ability of a hydrological model to integrate GIS for hydrologic data development, spatial model layers and interface may be considered as model selection criteria.

There are numerous criteria that can be used for choosing the "right" hydrologic model. These criteria are always project-dependent, since every project has its own specific requirements and needs. Some models are data intensive that often does not exist or are not available in full. Therefore to select a model to accomplish the objectives of this research in the Hare watershed as case study, the following selection criteria were formulated against which models could be assessed for suitability.

- The model must be able to simulate agricultural/rural areas because the Hare watershed can be classified as agricultural watershed
- It should be able to simulate different components of the streamflow including surface runoff, lateral flow and base flow that are important components of the flow in perennial rivers in tropical catchments such as the Hare watershed.
- It should incorporate tools that would allow land use and land cover, and climate changes to enable assessment of the impacts of land use and land cover, and climate changes on water resources.
- The minimum input data requirements for the model must be available or can be met with some efforts through gathering data from a data-poor watershed such as the Hare
- Its temporal scale should be long term, continuous and able to simulate on daily bases for water budget analyses at watershed and sub-watershed levels
- The model must be readily and freely available, both for research and for future use in Ethiopia.
- The model should be one that can be applied over a range of watershed sizes from small to large catchments/basins so that the Hare watershed and other similar watersheds could be modelled

A two-level selection approach was used to objectively determine the most suitable models for this research. At the first preliminary screening level a large number of existing hydrologic models were reviewed according to the above pre-set fundamental criteria. Empirical black box rainfall-runoff models were not studied as they are unable to give robust predictions of future change i.e. when going outside their range of calibration. Lumped models were considered inappropriate due to their spatial discretization and fully distributed models were not considered too due to intensive data requirement as opposed to scarce data availability at the studied watershed. At the second level, six selected models were then reviewed in detail according to the above evaluation criteria reflecting different aspects of specific the research's requirements (Table 4.1). On top of the above criteria, temporal and spatial scales, processes modeled, price, technical support, set-up time, expertise required, and documentation available were also considered.

Table 4.1 Description of six screened semi-distributed hydrological models

Description	**SWAT**	**HSPF**	**HEC-HMS**	**WaSiM-ETH**	**DWSM**	**HBV**
Model Type	Semi-distributed Physically-based long-term	Semi-distributed conceptual model	Semi-distributed Physically-based	Semi-distributed Physically-based modular	Semi-distributed Physically-based	Semi-distributed conceptual model
Model objective	predict the impact of land management practices on water and sediment	Simulates watershed hydrology, and sediment-chemical interactions	Simulate the rainfall-runoff process of dendritic watersheds	Simulate watershed water balance	Simulations of surface and subsurface storm water runoff , flood, sediment transport,	Simulate rainfall-runoff process and floods
Temporal scale	Day^{+}	Flexible	Day^{-}	Day^{+}	Day^{+}	Day^{-}
Watershed representation	Sub-watersheds grouped based on climate, HRU, ponds, groundwater, and main Channel	Uses sub-basins as primary hydrological units	Uses sub-basins as primary hydrological units	Grid based	Sub-watersheds (1-D overland elements, channel, and reservoir units.	Uses sub-basins as primary hydrological units
Process modelled	Continuous	Continuous & event	Continuous & event	Continuous	Single event	Continuous & event
Runoff on overland	Runoff volume using CN and flow peak using Rational formula.	Chezy-Manning equation.	Clark's, Snyder's, SCS UHs, ModClark Kinematic wave	using saturation time after Peschke (1977)	Kinematic wave equations	Uses response function to transform excess rainfall to runoff
Evapo-transpiration	Hargreaves, Priestley-Taylor & Penman	Hamon , Jensen methods	Monthly average	Penman-Monteith, Wendling, Hamon	No information	Monthly average
Subsurface flow	Lateral s flow using kinematic storage model and groundwater flow using empirical relations.	Interflow outflow, and groundwater flow using empirical relations	Constant monthly, Exponential recession or Linear reservoir	Empirical equation	Combined interflow, and baseflow using kinematic storage equation	Simple functions of actual water storage in a soil box
Water Routing	Variable storage coefficient method Or Muskingum method	Inflows enter upstream point, and outflow is a function of reach volume	Kinematic wave, Lag, Muskingum, Muskingum-Cunge	Translation-retention approach using hydraulic parameters	Same as overland flow	Muskingum method or simple time lag
Management practices	Agricultural mang't, Tillage, irrigation, etc	Agricultural management, irrigation,	Account human impact on runoff	Irrigation, Water management options	Detention basins, alternative ground covers,	Different management practices
References	Neitsch et al. (2005)	Bicknell et al. (2001)	US-ACE (2001)	Schulla, 2000	Borah and Bera (2004)	SHMI (2003)

From the preceding sections and considering the criteria developed, SWAT2005 and HSPF models have been selected for this research. The basic reason, amongst others, is in an economically poor region like Ethiopia, the data requirements of these models can be acquired from second sources and some efforts from the field and the models will have potentially important pragmatic advantages for their wider future use in the region.

4.4 Description of Selected Models

4.4.1 The SWAT Model

The Soil and Water Assessment Tool (SWAT) model developed at USDA-ARS (Arnold et al., 1998) in a modelling experience that span roughly 30 years. The model is semi-distributed physically based simulation model and can predict the impact of land use change and management practices on hydrological regimes in watersheds with varying soils, land use and management conditions over long periods and primarily as a strategic planning tool. It incorporates features of several ARS models and is a direct outgrowth of the SWRRB model (Arnold and Williams, 1987). The specific models that contributed significantly to the development of SWAT were CREAMS model (Knisel, 1980), GLEAMS model (Leonard et al., 1987) and EPIC model (Izaurralde et al., 2006), which was originally called the Erosion Productivity Impact Calculator (Williams, 1990).

A SWAT2005 interface compatible with ArcGIS version 9.2 (ArcSWAT 2.1.4) has recently been developed that uses a geo-database approach and a programming structure consistent with component object model protocol (Olivera et al., 2006; SWAT, 2007a). In SWAT2005, the impacts of spatial variations in topography, land use, soil and other watershed characteristics on hydrology are considered in subdivisions. There are two-level scales of subdivisions: (1) a watershed is divided into a number of sub-watersheds based upon drainage areas of the tributaries, and (2) each sub-watershed is further divided into a number of Hydrologic Response Units (HRUs) based on land use and land cover, soil and slope characteristics. The model operates on a daily time step, allows a basin to be subdivided into natural sub-watersheds, and is characterized by its focus on land management, water quality loadings, and continuous simulation over long time spans.

The SWAT2005 model was built with state-of-the-art components with an attempt to simulate the processes physically and realistically. The model combines empirical and physically-based equations, uses readily available inputs, and enables users to study long-term impacts. It simulates eight major components: hydrology, weather, sedimentation, soil temperature, crop growth, nutrients, pesticides, and agricultural management (Neitsch et al., 2005). Major hydrologic processes that can be simulated by the model include evapotranspiration, surface runoff, infiltration, percolation, shallow aquifer and deep aquifer flow, and channel routing (Arnold et al., 1996). The simulation of the processes can be done in four subsystems: surface soil, intermediate zone, shallow and deep aquifers, and open channels. Stream flow in a main channel is determined by three sources: surface runoff, lateral flow and base-flow from shallow aquifers.

The model has been used to predict streamflow which were compared favourably with measured data for a variety of watershed scales (Saleh et al., 2000; Santhi et al., 2001; Van Liew and Garbrecht, 2003; Govender and Everson, 2005), to predict various impacts of land management on water quantity (Srinivasan and Arnold 1994; Muttiah and Wurbs, 2002), to quantify the environmental benefits of conservation practices at both the national and watershed scales (Mausbach and Dedrick, 2004), to estimate base flow and/or groundwater flow (Arnold et al., 2000; Kalin and Hantush, 2006), to predict potential climate change impacts on water resource (Rosenberg et al., 2003; Jha et al., 2004; Gosain, et al. 2006) and assess the impact of land use changes on the annual water balance and temporal runoff dynamics (Fohrer et al., 2001; Fohrer and Frede, 2002; Fohrer et al., 2005).

Similarly, SWAT has been successfully applied in Ethiopian watersheds too. For instance the model was used in Blue Nile Basin (Sirak, 2007; Shimelis, 2008); central Ethiopia (Alamirew, 2006; Lijalem, 2006) and other part of the country to model the hydrological process, sediment yield and estimate water balance. The overall performance of the model in most cases appears to be reasonable.

Gosain et al. (2005) assessed SWAT's ability to simulate return flow after the introduction of canal irrigation in a basin in Andra Pradesh, India. SWAT provided the assistance water managers needed in planning and managing their water resources under various scenarios. Santhi et al. (2005) describe a new canal irrigation routine that was used in SWAT. Volk et al. (2007) and van Griensven et al. (2006a) also described SWAT application approaches within in the context of the EU Water Framework Directive.

4.4.2 The HSPF Model

Hydrological Simulation Program—FORTRAN (HSPF) is a comprehensive, continuous watershed scale model developed by the United States Environmental Protection Agency for simulating many processes related to water quantity and quality in watersheds of almost any size and complexity. Values of many HSPF parameters can be conceived to index properties of specific factors that influence events such as water storage and fluxes in the land phase of the hydrologic cycle. Thus, one may categorize HSPF as moderately physically based model.

The model is a fully-integrated component of the BASINS (Better Assessment Science Integrating Point and Nonpoint Sources) system but can be run stand-alone (Bicknel et al., 2001). The model is comprised of three main modules viz. PERLND, IMPLND, and RCHRES which help simulate pervious land segments, impervious land segments, and free-flow reaches/mixed reservoirs, respectively. PERLNDs as defined in the model reflect three hydrologic characteristics--land cover or land use, surface slope, and soil permeability. The RCHRES module simulates the processes that occur in a single reach of an open channel or well-mixed impoundment.

As part of the model development process, many components of the BASINS 4.0 system, namely Watershed Data Management Utility (WDMUtil) for pre-processing, GENeration and analysis of model simulation SCeNarios (GenScn) for post-processing and an Expert System for HSPF hydrology calibration (HSPEXP) (Lumb, 1994) can be used during the process of modeling using HSPF. The WDMUtil program allows users to import available meteorological data and data sets of various time steps and formats into WDM files. GenScn is a graphic user interface based program for creating simulation scenarios, analyzing the results and comparing scenarios. HSPEXP interactively allows the user to edit the input sequences of HSPF, simulates with HSPF, plots the output from the HSPF against different observed values and computes error statistics.

Currently, the Windows version of HSPF (WinHSPF) that is designed to work with version 12.0 of the HSPF model and integrates GIS for landscape data analysis including land use distribution, elevation data, and drainage stream network characteristics may be employed to prepare many of the input data the model requires. Within the BASINS system, WinHSPF is intended to be used in conjunction with the interactive program GenScn. HSPF is capable of simulating a single watershed or a system of multiple hydrologically connected sub-watersheds and is designed for evaluating alternative management scenarios. Similar to SWAT2005, four types of digital spatial data are used in BASINS/WinHSPF to construct a User Control Input (UCI) file for an initial HSPF simulation run. These are land use data, DEM, user-specified outlet points (stream-gage locations), meteorological data, and user-specified sub-basin threshold-area size of concern in the watershed and its reaches. Detailed information about the structure and functioning modules of HSPF can be found in Bicknel et al., (2001).

HSPF has been widely applied for different analysis with diverse geographical characteristics. Some of these applications include Laroche, et.al. (1996); Jacomino and Fields (1997); Brun and Band (2000); Johnson et al. (2001); Albek et al., (2004), and Singh et al., (2005). From calibration and validation of daily, weekly, and monthly stream flows, Laroche et al. (1996) found that as the time interval got smaller, the model became less precise. Bergman and Donnangelo (2000) used HSPF to regionalize its parameters in ungauged portion of a basin through calibration and validation on a few of the tributary watersheds. On the other hand, Gericke, et.al (2004) discussed the application of HSPF to model the hydrology of a River Basin in South Africa. They highlighted the model can contribute for effective management of the hydrological cycles of the Basin and it can be used effectively to determine and evaluate environmental management and basin policies of watershed management agencies

Singh et al., (2005) used SWAT and HSPF to simulate the hydrology of Iroquois River Watershed in the USA. They indicated that calibrated SWAT and HSPF models can simulate the average annual flows satisfactorily for period outside the calibration period. Similarly, Borah and Bera (2004) reviewed and discussed the applications and performances of SWAT, HSPF, and DWSM. In that review, conceptual and mathematical bases of SWAT, HSPF, and DWSM were found to be sound, respectively, for long−term continuous simulations of predominantly agricultural watersheds, long−term continuous simulations of mixed agricultural and urban watersheds, and storm (rainfall) event simulations of agricultural and rural watersheds.

4.5 Hydrological Processes Modelled

The hydrological processes simulated by both SWAT2005 and HSPF include precipitation, evapotranspiration, surface run-off, lateral subsurface flow, groundwater flow and river flow. Both models are among the few watershed models capable of simulating land processes and receiving water processes simultaneously. They have similarity in simulating both peak flow and low flow, at a variety of time-steps, the hydraulics of complex natural and man-made drainage networks etc. However, in SWAT2005, a daily water budget is established for each HRU based on these parameters that increases accuracy and gives a much better physical description of the water balance. The following figure displays the pathways for water movement within SWAT2005.

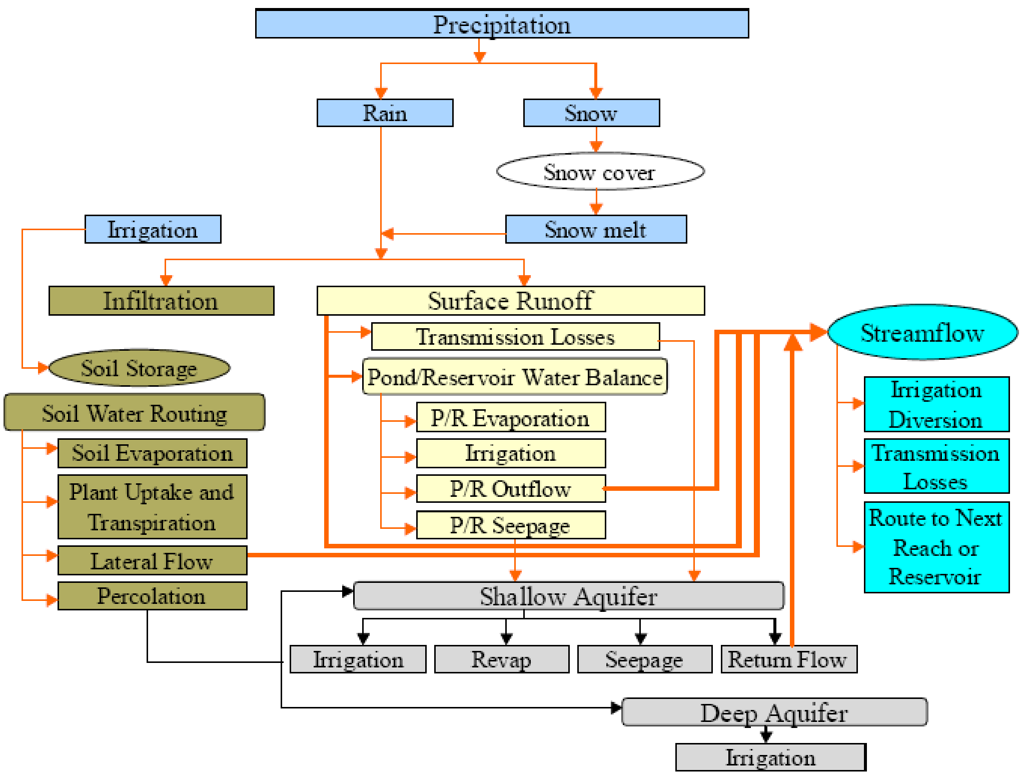


Figure 4.2 Pathways for water movement within SWAT2005 (after Neitsch et al., 2005)

On the other hand, HSPF uses smaller sub-watersheds to better consider the details of spatial effects of watershed parameters. However, the process simulated in HSPF for the pervious land segment (PERLND) module land segment is given in Figure 4.3. A PERLND is a land-segment subdivision of the simulated watershed where infiltration is possible. The shaded area is below the surface of the land. Evapotranspiration moves to the left and up; numbers on the left indicate the order that evaporation is taken from the PERLND. Runoff moves to the right. When the interception storage is full, precipitation is routed directly to the land surface. Once on the land surface, precipitation may infiltrate, remain in surface detention storage, or run off directly to the river channel.

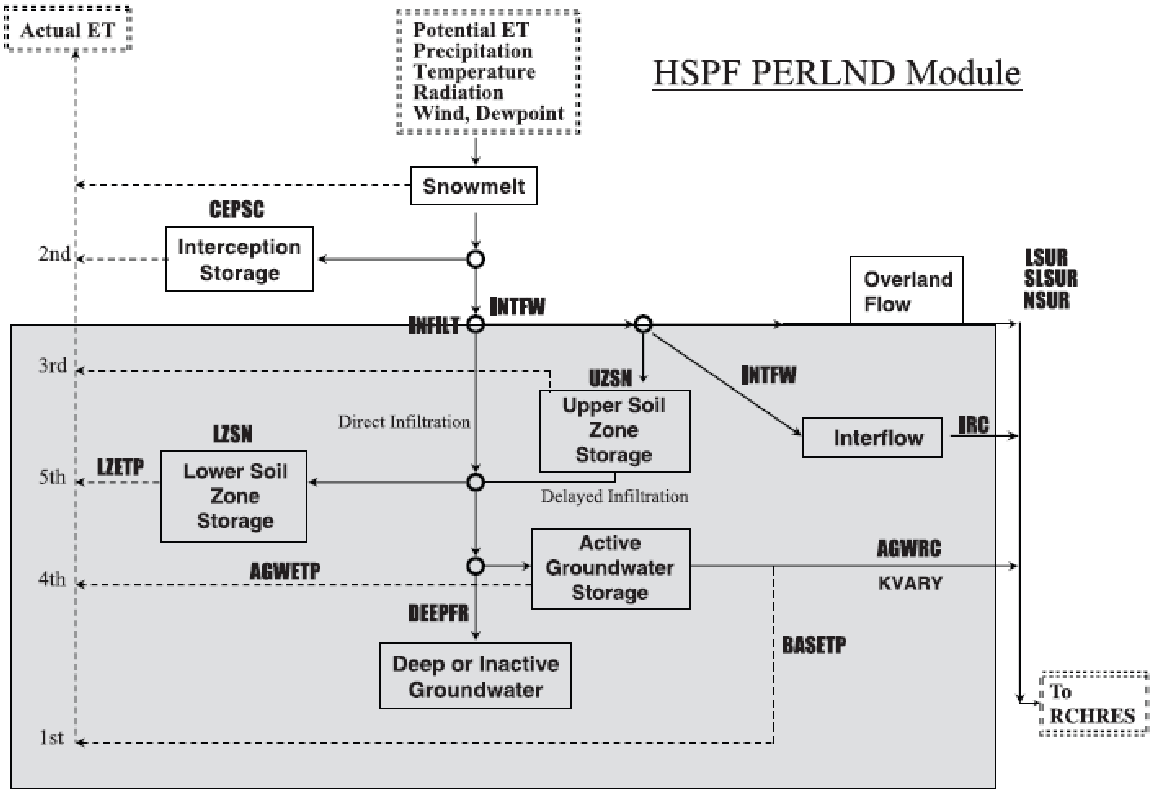


Figure 4.3 Process simulated in HSPF for the pervious land segment (Bicknel et al., 2001)

Generally, simulation of the hydrology of a watershed can be separated in two major components: The **land phase** and the **routing phase** of the hydrologic cycle. Each of these phases is described briefly here after. ***The land phase of the hydrologic cycle*** of SWAT2005 is simulated based on the water balance equation (3.1).

$$SW_t = SW_o + \sum_{i=1}^{t} \left(R_d - Q_s - E_a - W_s - Q_g\right) \tag{4.1}$$

Where SW_t is the final soil water content (mm), SW_0 is the initial soil water content (mm), t is the time (days), R_d is the amount of precipitation on day i (mm), Q_s is the amount of surface runoff on day i (mm), Ea is the amount of evapotranspiration on day i (mm), W_s is the amount of percolation and bypass flow exiting the soil profile bottom on day i (mm), and Q_g is the amount of return flow on day i (mm).

For a particular interest of this research, the major land phase components of the hydrologic cycle for both models are discussed as follows. More detailed theoretical background on the models components, descriptions of hydrological processes and Input/output file documentations are found in Neitsch et al. (2005) for SWAT2005 and Bicknel et al., (2001) for HSPF.

4.5.1 Surface Runoff Generation

Surface runoff or overland flow is a flow that occurs along a sloping surface and it occurs whenever the rate of water application to the ground surface exceeds the rate of infiltration. It is the major component of the hydrologic cycle.

SWAT2005 provides two surface runoff computation methods; a modification of the Soil Conservation Service (SCS) Curve Number (CN) method (USDA SCS, 1972) or the Green & Ampt infiltration method (Green and Ampt, 1911). The CN method was initially developed for small agricultural watersheds and the CN varies non-linearly with the moisture content of the soil. It drops to zero as the soil approaches the wilting point and increases to near 100 as the soil approaches saturation, with higher CNs associated with higher runoff potential watershed. This method is widely used (Arnold et al., 1998; Lukman, 2003; Garen and Daniel, 2005). In this method, the ratio of actual retention to maximum retention is assumed to be equal to the ratio of direct runoff to rainfall minus initial abstraction. This can be mathematically expressed as (USDA, 1985)

$$Q_s = \frac{(R_d - I_a)^2}{(R_d - I_a + S)} \tag{4.2}$$

For $R_d > I_a$
$Q = 0$, for $R_d \leq I_a$

Where Q_s is the accumulated runoff (mm), R_d the rainfall depth for the day (mm), I_a is initial abstraction (mm, surface storage, canopy interception, infiltration prior to runoff) and S is the potential maximum moisture retention after runoff begins (mm)

To remove the necessity for an independent estimation of initial abstraction, a linear relationship between I_a and S was suggested by SCS as, $I_a = \lambda S$ and where λ is an initial abstraction ratio. The values of λ vary in the range of 0 and 0.3. The variable S varies with antecedent soil moisture and other variables, it can be estimated as;

$$S = \frac{25400}{CN} - 254 \tag{4.3}$$

With this consideration the surface runoff equation becomes:

$$Q_s = \frac{(R_d - 0.2S)^2}{(R_d + 0.8S)} \tag{4.4}$$

The CNs for different land use and land cover, soil groups and antecedent moisture conditions are provided with SWAT2005 manual that takes in account of soil infiltration rate when thoroughly wetted, and slope adjustments (Williams, 1995).

On the other hand, in HSPF, overland flow is treated as a turbulent flow process. Surface runoff is simulated using the Chezy-Manning equation, which is parameterized as a function of a surface routing variable. The surface routing variable, in turn, is computed as a function of the length of the flow path, the Manning's roughness, and the slope of the overland plane. Inflow to the surface detention storage is added to existing storage to make up the water available for infiltration and runoff. Moisture that directly infiltrates from the surface moves to the lower zone and groundwater storages. Other water may go to the upper zone storage, may be routed as runoff from surface detention or interflow storage, or may stay on the overland flow plane, from which it runs off or infiltrates at a later time. The purpose of subroutine Surface Runoff (PROUTE) is to determine how much potential surface detention runs off in one simulation interval. The rate of overland flow discharge is determined by the following equation (Bicknel et al., 2001).

For SURSM < SURSE

$$SURO = DELT60 \cdot SRC \cdot \left(SURSM \cdot \left(1.0 + 0.6(SURSM/SURSE)\right)^3\right)^{1.67} \tag{4.5}$$

For SURSM >= SURSE

$$SURO = DELT60 \cdot SRC \cdot (SURSM \cdot 1.6)^{1.67} \quad (4.6)$$

Where SURO is surface outflow (in/interval), DELT60 is number of hr per interval (hr/interval), SRC is routing variable (calculated as a function of length, slope and rate moisture supplied to overland flow, SURSM is mean surface detention storage over the time interval (in) and SURSE is equilibrium surface detention storage (inches) for current supply rate

4.5.2 Computation of Evapotranspiration

Evapotranspiration is a collective term that includes all processes by which water at the earth's surface is converted to water vapor. This expression combines evaporation and transpiration. By evaporation Shahin (2002) refers to "evaporation from open water systems, like natural lakes and man-made pools and reservoirs, rivers, bare soil with water tables at or close to the land surface, and impervious surfaces like roofs and roads" and where evaporation from vegetated surfaces, forests and woodland is accompanied by transpiration, it is referred to as evapotranspiration. Consequently, Potential evapotranspiration (PET) is defined as the rate at which evapotranspiration would occur from a short green crop, completely shading the ground, of uniform height and never short of water (Penman, 1956).

SWAT2005 offers three models for estimating PET: the Penman-Monteith model (Monteith, 1965), Priestley-Taylor model (Priestley and Taylor, 1972), and Hargreaves model (Hargreaves and Samani, 1985). Once PET is determined, SWAT2005 calculates the actual evaporation from a given plant canopy using an approach similar to that of Richtie (1972).

The WDMUtil can be used to compute PET using the Hamon method (Hamon, 1963) and Jensen method (Jensen, and Haise, 1963) so that computed value can be used as input for HSPF. Here, there are two separate issues involved in estimating evapotranspiration. First, PET must be estimated using either of the above methods Second, actual ET must be calculated, usually as a function of moisture storages and the PET. The actual ET is estimated by trying to meet the demand from five sources including ET from the active groundwater outflow/baseflow, interception storage, upper zone, active groundwater storage and lower zone.

4.5.3 Water Movement in Soil

Water maintained in the soil profile after infiltration can flow under saturated or unsaturated conditions. In saturated soils, flow is driven by gravity and usually occurs in the downward direction. Unsaturated flow on the other hand, is caused by gradients arising due to adjacent areas of high and low water content and may occur in any direction.

SWAT2005 directly simulates saturated flow if the water content is superior to the field capacity. The model records the water contents of the different soil layers (1 to 10) but assumes that the water is uniformly distributed within a given layer. Unsaturated flow between layers is indirectly modeled with the depth distribution of plant water uptake and the depth distribution of soil water evaporation. SWAT2005 allows water to percolate from one layer if the water content exceeds the field capacity water content for this layer. The amount of water that moves from one layer to the underlying layer is calculated using storage routing methodology. Water that percolates to the next layer is computed as:

$$W_{p,ly} = SW_{ly,excess}\left[1 - exp\left(\frac{-\Delta t}{TT_p}\right)\right] \tag{4.7}$$

Where the travel time for percolation is unique for each layer and is calculated as:

$$TT_p = \frac{Sat_{ly} - FC_{ly}}{K_s} \tag{4.8}$$

Where $W_{p,ly}$ is the amount of water percolating to the underlying soil layer on a given day (mm), $SW_{ly,excess}$ is the drainable volume of water in the soil layer on a given day (mm), Δt is the length of the time step (hrs), TT_p is the travel time for percolation (hrs), Sat_{ly} is the amount of water in the soil layer when completely saturated (mm), FC_{ly} is the water content of the soil layer at field capacity (mm), and K_s is the saturated hydraulic conductivity for the layer (mm·hrs^{-1}).

Water that percolates out of the lowest soil layer enters the vadose zone (the unsaturated zone between the bottom of the soil profile and the top of the aquifer). SWAT2005 also applies a multiplayer storage routing technique to partition drainable soil water content for each layer into other components, which are lateral subsurface flow and percolation into the layer below.

In HSPF however, the water movement into the soil and through it is modeled by dividing the soil into an upper, lower and ground water zone. The water content in the upper and lower layers is represented by nominal storage parameters called UZSN and LZSN respectively. Initial values of these parameters are estimated by taking into account precipitation values, and final values are obtained through calibration. Water infiltrating through the surface and percolating from the upper zone storage may become stored within the lower zone storage, flow to active groundwater storage, or may be lost by deep percolation. The water that reaches the lower zone is subject to evapotranspiration. The water holding capacity of the two soil storages, upper zone and lower zone, in module section PERLND is defined in terms of nominal capacities (Bicknel et al., 2001).

In HSPF Lower Zone (LZONE) subroutine determines the quantity of infiltrated and percolated water which enters the lower zone. The infiltrated moisture supply is determined in subroutine DISPOS. The percolated moisture from the upper zone is found in subroutine UZONE. The fraction of the lower zone inflow, which is the sum of direct infiltration, percolation, lower zone lateral inflow, and irrigation application, that enters the lower zone storage (LZS) is based on the lower zone storage ratio of LZS/LZSN where LZSN is the lower zone nominal capacity. The inflowing fraction is determined empirically by:

$$LZFRAC = 1 - LZRAT \cdot (1/(1 + INDX))^{INDX} \tag{4.9}$$

When LZRAT is less than 1.0, and by

$$LZFRAC = (1/(1 + INDX))^{INDX}$$

When LZRAT is greater than 1.0, INDX is defined by:

$$LZFRAC = 1.5 \cdot ABS(LAZART - 1) + 1$$

Where LZFRAC is fraction of infiltration, percolation, and lower zone lateral inflow that enters LZS, LZRAT is equals LZS/LZSN and ABS is function for determining absolute value

4.5.4 Lateral Subsurface Flow

Lateral subsurface flow or interflow is streamflow contribution which originates below the surface but above the zone where rocks are saturated with water. Interflow in the soil profile is calculated simultaneously with redistribution. It can have an important influence on storm hydrographs particularly when vertical percolation is retarded by a shallow, less permeable soil layer.

SWAT2005 incorporates a kinematic storage model (Sloan and Moore, 1984) to compute subsurface flow as a function of the drainable volume of water, saturated hydraulic conductivity, soil slope, hill slope length, and drainable porosity. This model simulates subsurface flow in a two-dimensional cross-section along a flow path down a steep hill-slope. The kinematic wave approximation of saturated subsurface/lateral flow assumes that the lines of flow in the saturated zone are parallel to the impermeable boundary and the hydraulic gradient equals the slope of the bed. The equation to compute lateral flow is given as:

$$q_l = 0.024\left[\frac{2 \cdot SW \cdot K_s \cdot \ sl}{\emptyset_d \cdot L_h}\right] \tag{4.10}$$

Where, q_l is lateral flow (mm d^{-1}), SW is drainable volume of soil water (mm), sl is slope (m/m), ϕ_d is drainable porosity (mm/mm), K_s is saturated hydraulic conductivity (mm hrs^{-1}) and L_h is the hill slope length (m).

Lateral flow is significant in areas with soils having high hydraulic conductivities in surface layers and an impermeable or semi permeable layer at a shallow depth. In such a system, rainfall will percolate vertically until it encounters the impermeable layer. The water then ponds above the impermeable layer forming a saturated zone of water and this saturated zone is then the source of water for lateral subsurface flow.

On the other hand, in HSPF, additions to the interflow component are retained in storage or routed as outflow from the land segment. Inflows to the interflow component may occur from the surface or from upslope external lateral flows. The purpose of this subroutine is to determine the amount of interflow and to update the storage. The calculation of interflow outflow assumes a linear relationship to storage. Thus outflow is a function of a recession parameter, inflow, and storage. Moisture that remains will occupy interflow storage. Interflow discharge is calculated by:

$$IFWO = (IFWK1 \cdot INFLW) + (IFWK2 \cdot IFWS) \tag{4.11}$$

IFWK1, IFWK2 and KIFW are variables determined by:

IFWK1 = 1.0 - (IFWK2/KIFW)
IFWK2 = 1.0 - EXP (-KIFW)
KIFW = -ALOG (IRC)*DELT60/24.0

Where IFWO is interflow outflow (in/interval), INFLO is inflow into interflow storage (including lateral inflow) (in/interval), IFWS is interflow storage at the start of the interval (inches), IRC is interflow recession parameter (per day), DELT60 is number of hr per interval, 24.0 is number of hours per day, EXP is exponential function and ALOG is natural logarithm function

4.5.5 Baseflow Estimation

Return flow or baseflow is the volume of stream flow originating from groundwater. It is assumed that 50% of the water that percolates down to shallow ground water contributes to baseflow. The amount of baseflow a stream receives is closely linked to the permeability of soil in the watershed.

SWAT2005 partitions groundwater into two aquifer systems: a shallow, unconfined aquifer which contributes return flow to streams within the watershed and a deep, confined aquifer which contributes return flow to streams outside the watershed (Arnold et al., 1993). The latter can be seen as a loss of the watershed system. Water percolating past the bottom of the root zone is partitioned into two fractions and each fraction becomes recharge for one of the aquifers. In addition to return flow, water stored in the shallow aquifer may replenish moisture in the soil profile in very dry conditions or be directly removed by plant. Water in the shallow or deep aquifer may be removed by pumping for irrigation or other uses.

The contribution of ground water to stream flow is simulated by creating a shallow aquifer storage which is recharged by percolation from the unsaturated zone, and discharges to the reach of the watershed. The water balance for the shallow aquifer is:

$$Aq_{sh,i} = Aq_{sh,i-1} + W_{rec} - Q_g - W_{rev} - W_d - WU_{sa} \qquad (4.12)$$

And groundwater flow into the main channel on day "i" is calculated using:

$$Q_{g,i} = Q_{g,i} * e^{-\propto\Delta t} + W_{rec}(1 - e^{-\propto\Delta t}) \qquad (4.13)$$

Where $Aq_{sh,I}$ and $Aq_{sh,i-1}$is the shallow aquifer storage (mm) on day i and i-1 respectively, W_{rec} is the recharge entering the aquifer on day i (mm), Q_g is the groundwater flow or base flow, into the main channel on day i (mm), W_{rev} is the amount of water moving into the soil zone in response to water deficiencies on day i (mm), W_d is the amount of water percolating from the shallow aquifer into the deep aquifer on day i (mm), WU_{sa} is the water use from the shallow aquifer (mm), α is the recession constant which describes the lag flow from the aquifer and Δt is the time step and α can be best estimated by analyzing measured stream flow during periods of no recharge in the watershed.

On the other hand, in HSPF, the quantity of direct infiltration plus percolation from the upper zone which does not go to the lower zone will be inflow to either inactive or active groundwater. The distribution to active and inactive groundwater is user designated by fraction of the groundwater inflow which goes to inactive groundwater (DEEPFR). The remaining portion of the percolating water plus all lateral inflow and/or irrigation application make up the total inflow to the active groundwater storage. The outflow from active groundwater storage is based on a simplified model. It assumes that the discharge of an aquifer is proportional to the product of the cross-sectional area and the energy gradient of the flow. Active groundwater eventually reappears as baseflow, and may be subject to evapotranspiration, but deep percolation is considered lost from the simulated system. The groundwater outflow is estimated b the following equation:

$$AGWO = KGW \cdot (1 + KVARY \cdot GWVS) \cdot AGWS \quad (4.14)$$

Where AGWO is active groundwater outflow (in/interval), KGW is groundwater outflow recession parameter (/interval), KVARY is parameter which can make active groundwater storage to outflow relation nonlinear (/inches), GWVS is index to groundwater slope (inches) and AGWS is active groundwater storage at the start of the interval (inches)

4.5.6 Flow Routing

The second component during the simulation of the hydrology of a watershed is the routing phase of the hydrologic cycle**.** As water flows downstream, a portion may be lost due to evaporation and transmission through the bed of the channel. Another potential loss is removal of water from the channel for agricultural or human use. Flow may be supplemented by the fall of rain directly on the channel and/or addition of water from point source discharges. Two general approaches are use for solving the unsteady flow problem in channels – hydrologic and hydraulic. The hydrologic approach is based on the storage concept while the hydraulic approach uses principles of mass and momentum conservation. Usually, the Muskingum method is used for the hydrologic approach, while the kinematic wave method is used for the hydraulic transformation.

SWAT2005 uses Manning's equation to define the rate and velocity of flow. Once the model determines flow to the main channel, it is routed through the stream network of the watershed using a command structure similar to that of HYMO (a problem-oriented computer language for building hydrologic models) (Williams and Hann, 1973). Arnold et al. (1996) developed the Routing Outputs to Outlet (ROTO) model that latter merged to SWAT2005 to route the flows through channels and reservoirs in order to support an assessment of the downstream impact of water management. Flow is routed through the channel using a variable storage coefficient method developed by Williams (1969) or the Muskingum routing method.

Conversely, HSPF a channel reach is modeled as a one dimensional element consisting of a single zone situated between two nodes. Flow rate and depth are simulated at the nodes; the zone is associated with storage. The model uses a technique falls in the class known as "storage routing" or "kinematic wave" methods to route water from one reach to the next during stream processes. Storage routing is similar in concept to Muskingum routing method. However, the inflow hydrograph to the detention watershed corresponds to the hydrograph at the upstream location, and the hydrograph for the outflow from the watershed corresponds to the downstream hydrograph.

Beside the above processes the models give different options to simulate plant growth and management options. For instance, SWAT2005 utilizes a single plant growth model to simulate all types of land covers. Plant growth is simulated using a simplification of the EPIC crop model (Williams et al., 1984). The model is able to differentiate between annual and perennial plants. The plant growth model is used to assess removal of water and nutrients from the root zone, transpiration, and biomass/yield production. The model uses Monteith’s approach to estimate potential biomass (Monteith, 1977) coupled with stress adjustments for water, temperature and nutrients. The leaf area index is simulated as a function of heat units and varies between plant-specific minimum and maximum values.

Furthermore, SWAT2005 allows very detailed management information to be incorporated into a simulation. The model allows the user to define management practices taking place in every HRU. Conservation practices that can be accounted for include terraces, strip cropping, contouring, grassed waterways, filter strips, and conservation tillage. The user may define the beginning and the ending of the growing season; specify timing and amounts of fertilizer and irrigation applications as well as timing of tillage operations. Simulation of irrigation water on cropland can be simulated on the basis of five alternative sources: stream reach, reservoir, shallow aquifer, deep aquifer, or a water body source external to the watershed. The irrigation applications can be simulated for specific dates or with an auto-irrigation routine, which triggers irrigation events according to a water stress threshold.

However, in HSPF, effect of vegetation type, density, root growth, and stage of development along with the moisture characteristics of the soil layer is lumped into the parameter that controls actual ET from the lower zone storage. On the other hand, the model uses a Best Management Practice Evaluation module to simulate the effects of Best Management Practices by applying simple “removal” fractions to each constituent being modeled. A single instance of the module handles the transfer of all mass loads from any number of pervious or impervious lands to a single reach, as long as the same fractions are to be applied for each land use.

4.6 Models Input Data preparation and processing

4.6.1 General

In this research, ArcSWAT version 2.1.4 for SWAT2005 model, where the simulator is integrated with ArcGIS 9.2, and HSPF within the BASINS 4.2 platform of Map-window environment were employed. The basic data sets required to develop an input database for SWAT2005 and HSPF models are: geographic, meteorological, hydraulic and hydrological data as well as other watershed data. Required geographic data includes DEM, soil, and land use and land cover etc. Hydrological and hydraulic data includes stream flow gage data, stage-discharge relationship at cross-sections, and channel characteristics. Meteorological data required include rainfall, temperature, and other related data.

The key steps in modeling a watershed with both models are the mathematical representation of the watershed, the preparation of input meteorological and hydrological time series, the estimation of parameters and the calibration and validation process. Therefore, the first task in this research was therefore to characterize the watershed that involves collecting all necessary information about the watershed to establish baseline conditions for the assessment.

4.6.2 Climatic Input Data Processing

Records of hydrological processes such as precipitation and stream flow are usually short and often have missing observations. Therefore, one crucial step is to set the time reference of analysis in response to the data availability and then fill missing values within the time frame.

SWAT2005 includes the WXGEN weather generator model (Sharpley and Williams, 1990) to generate climatic data or to fill in gaps in measured records. The weather generator first independently generates precipitation for the day. Once the total amount of rainfall for the day is generated, the distribution of rainfall within the day is computed if the Green & Ampt method is used for infiltration, maximum temperature, minimum temperature, solar radiation and relative humidity are then generated based on the presence or absence of rain for the day. Finally, wind speed is generated independently. To Generate the data, weather parameters were developed by using the weather parameter calculator WXPARM (Williams, 1995) and dew point temperature calculator DEW02 (Liersch, 2003), which were downloaded from SWAT website (http://www.brc.tamus.edu/swat/soft_links.html).

For this research work the weather information considered was for the period of 1980-2005. Missing weather data were given a negative (-99.0) value that tells the weather generator of SWAT to generate weather data for that day. In SWAT daily values for weather are generated from average monthly values. The same weather generator technique has been applied for filling in maximum, minimum temperature, wind speed, relative humidity and solar radiation.

Climatic data input were obtained from Ethiopian National Meteorological Agency (NAMSA) for 15 nearby weather stations and data from other two recently established (Dorze and Shama) stations in the watershed were also used as supplementary data.

Table 4.2 Weather stations around Hare watershed

Station	*Latitude*	*Longitude*	*elevation*	*Annual average rainfall (mm)*
Arba Minch (AMU)	6^0 05’	$37^0$35’	1240	894.7
Arba Minch (Farm)	6^0 28’	$37^0$45’	1220	805.3
Bedessa	6^0 07’	$37^0$38’	1750	1160.2
Boditi School	6^0 57’	$37^0$51’	1860	1208.2
Chencha	6^0 15’	$37^0$34’	2680	1348.0
Dana I	6^0 32’	$37^0$50’	1340	1352.0
Dana II	6^0 32’	$37^0$50’	1340	1237.4
Daremal	6^0 15’	$37^0$14’	1320	732.5
Dinka	6^0 32’	$37^0$30’	2010	1279.7
Gesuba	6^0 07’	$37^0$38’	1710	1159.9
Humbo	6^0 40’	$37^0$45’	1590	1087.0
Kemba	6^0 03’	$37^0$10’	1850	1261.5
Mirab Abaya	6^0 18’	$37^0$45’	1260	745.8
Morka	6^0 26’	$37^0$24’	1400	1008.3
Saki	6^0 55’	$38^0$00’	1580	1072.0
Sodo	6^0 51’	$37^0$45’	1800	1121.5
Wajifo	6^0 28’	$37^0$45’	1240	896.4

To check the quality of the data cross correlation between Arba Minch, Chencha and Mirab Abaya weather stations, which are close to Hare watershed, has been performed. The result indicated that good monthly correlation exists among the stations that sufficiently signify strong spatial and temporal association between the stations and as a result all the stations have been used for simulation purpose.

Rainfall is a more difficult climatological phenomenon to study than temperature, because it is discontinuous with some days receiving no rainfall, while other days receive trace to abundant amount of rainfall. Consequently, developing adequate spatial and temporal rainfall coverage for the watershed was a challenge due to the fact that high difference in elevation between the upper and lower parts of the watershed. Due to this reason, an elevation-rainfall relation was established using the above stations and the SWAT2005 elevation bands were used to generate rainfall inputs for each sub-watershed based on their elevation. It is assumed that a lot of insight may be gained by studying the spatial and temporal patterns of rainfall.

Although, all stations were used to develop an elevation-rainfall relation at the study area; however for running the models only Arba Minch, Chencha and Mirab Abaya stations were employed. Figure 4.4 below shows the location of these stations.

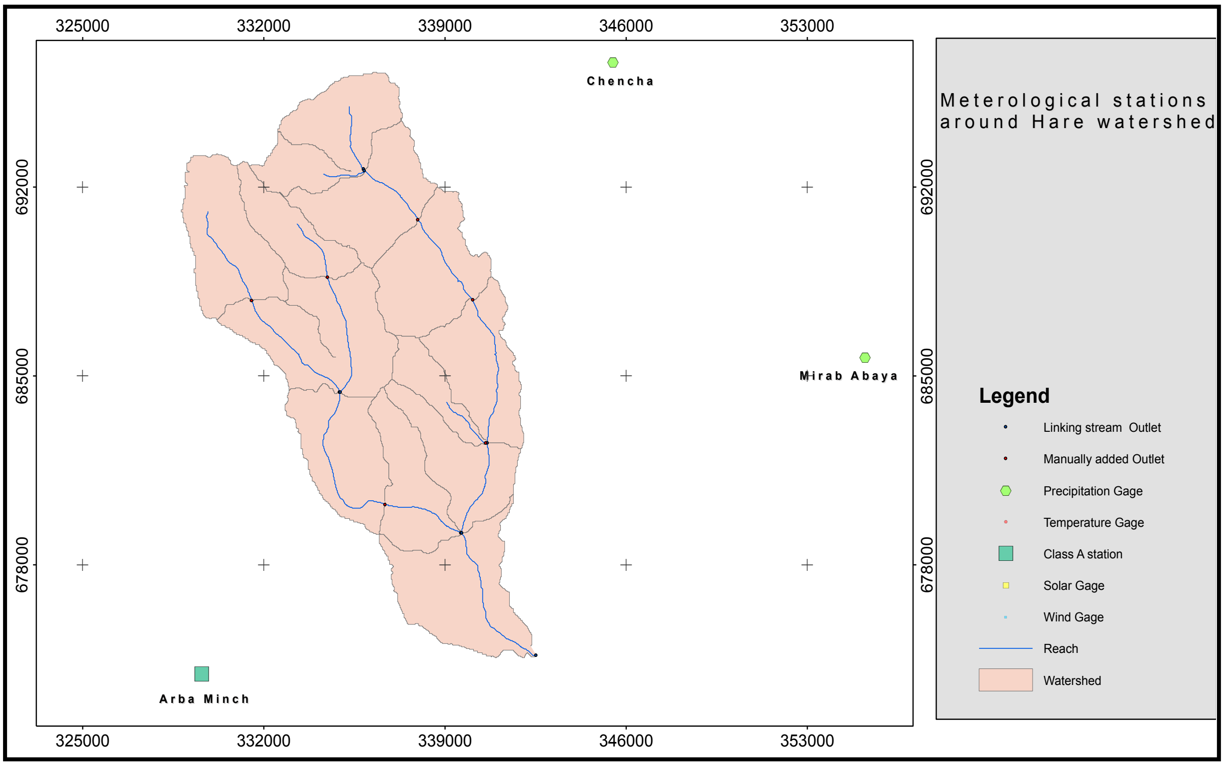


Figure 4.4 Location of weather stations

The SWAT2005 model allows values for daily rainfall, maximum/minimum air temperatures, solar radiation, wind speed and relative humidity to be input from records of observed data or generated during the simulation. These time series values are directly fed to the model as per the format protocol. Unlike SWAT2005, the time series fed to the HSPF model utilize the standalone data management program (WDMUtil). For use with HSPF, daily data of precipitation potential evaporation were disaggregated into hourly data using the Data Disaggregation Tool in the WDMUtil. Daily potential ET was computed using Jensen method integrated in the WDMUtil tool that uses daily maximum and minimum temperature, and solar radiation.

4.6.3 Soil Type Identification and Mapping

Soil data is important for sound natural resource management. The importance of soil properties stems from the important role they play in hydrological modeling. The use of models for the prediction of runoff and impacts of LUCC depends heavily on detailed data on soil physical properties and the understanding of these data. However, such data is unavailable in most part of Ethiopia including the study watershed. The only information available at the study area is the FAO soil map (1:1,000,000). Figure 4.5 presents soil map of Hare watershed, which is very course and doesn't give detailed information for hydrological modeling at a watershed level.

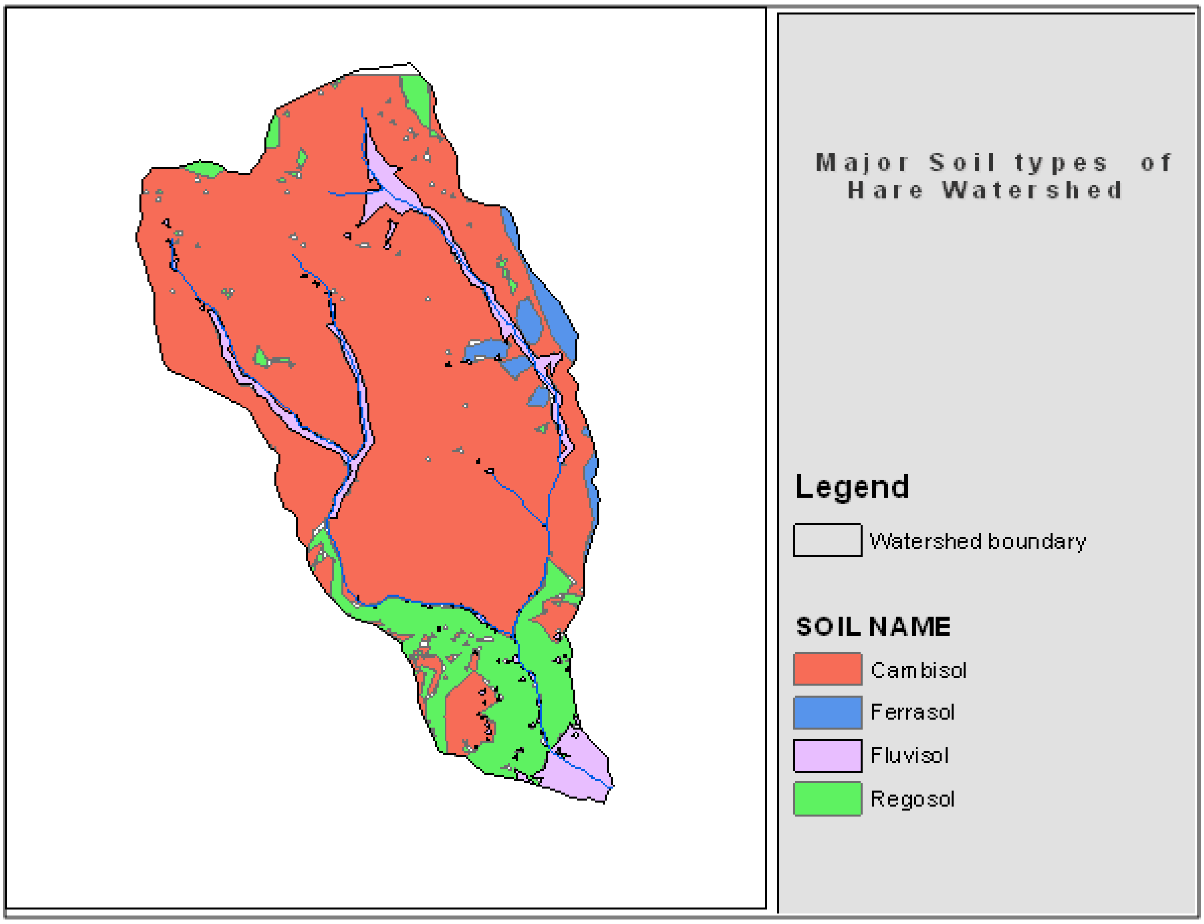


Figure 4.5 Major soil types of Hare watershed

The SWAT2005 model requires some details on physical and chemical properties of the soils the watershed being modeled. Therefore, the major concern of this research was to conduct field survey in order to acquire relevant physical and chemical properties required by the models throughout the watershed. Here, the methodology used in collecting field data and laboratory analysis of soil samples for particle size distribution (i.e. sand, silt and clay content), organic carbon, cations exchange capacity, pH, bulk density, and saturated hydraulic conductivity are elaborated. Consequently, the procedures used to generate polygons from point data are outlined. Lists soil properties required by the SWAT2005 model and the methods adopted to acquire them are presented in Appendix 4.4.

Primarily, a preliminary reconnaissance field survey was carried out to identify possible soil sampling sites and give a broad picture of the possible soil types that may be encountered at the site, followed by the detailed data collection and laboratory analysis. It is assumed that soils in each sub-watershed comprise soils that have been developed under similar conditions from similar parent material and therefore exhibit similar profile morphology or characteristics. This means that soils in the same sub-watershed have profiles that have been developed under similar drainage and climatic conditions; they have the same parent rock, same number of horizons or layers and corresponding layers have similar color, texture, consistency, structure and content of secondary minerals.

To enable soil data collection, a random sampling method was used to include all the land use and land cover classes and all sub-watersheds that were delineated. Totally 42 representative sites were identified throughout the watershed (Figure. 4.6) and a soil database was established through an intensive data collection from each of the sample sites.

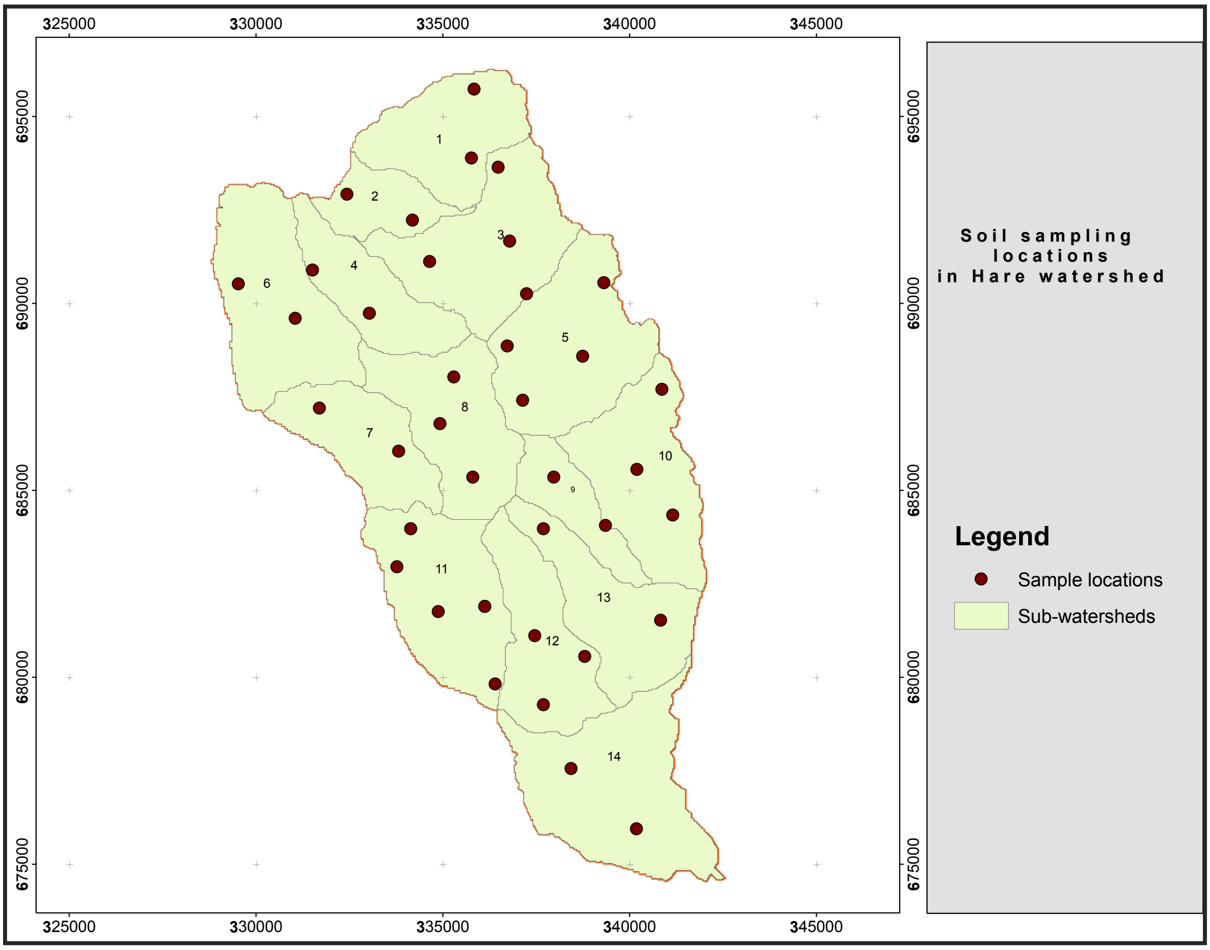
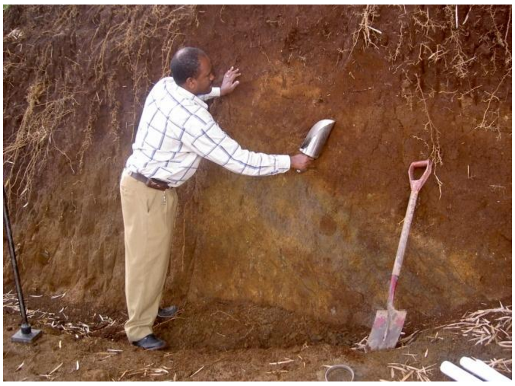


Figure 4.6 Soil sample location

Both disturbed and undisturbed soil samples were collected from first topsoil layer and then subsoil layers whose depths differ at different locations. The undisturbed samples were taken using a 10.0 cm long by 8.3 cm diameter cylindrical metal core with the help of a ring holder. The sampling core was inserted into the ring holder, which was then inverted onto the soil. The handle of the holder was then tapped gently with a mallet until the top of the soil core was about 0.5 cm below the soil surface. The soil around the holder was dug, the soil sample core brought out and excess soil cut off with a soil knife.

All disturbed soil samples were air dried in a laboratory and sieved (2 mm and 0.5 mm), analyzed for particle size distribution, pH, soil organic carbon and Soil Cation Exchange Capacity (CEC). The soil particle size together with its mineralogical composition largely determines the nature and behavior of soil. The three main fractions are clay (<2 μm), silt (2-60 μm) and sand (60-2000 μm). The hydrometer method was used in the laboratory to determine the particle size distribution. The plant available water is calculated by subtracting the fraction of water present at Wilting Point (WP) from that present at Field Capacity (FC) using the

Saxton, et al., (1985) method supplemented by standard values from literatures. Soil organic carbon is determined by oxidizing the organic matter with potassium dichromate in sulfuric acid solutions (FAO, 1972).


(a)


(b)

Figure 4.7 Soil sample collection (a) and soil sample preparation for analysis (b

On the other hand, soil PH and CEC were determined following the standard procedures of provided by FAO, (1972). After preparation of water extracts of the soil samples, the ethylenediaminettraacetate (EDTA) method was employed to determine calcium (Ca^{2+}) and magnesium (Mg^{2+}) and flame photometer method was used to determine of sodium (Na^{+}) and potassium (K^{+}). After calculation the mili-equivalent per 100g (meq/100g) for each cation, they were summed up to get CEC. Soil PH was determined from prepared soil suspension using a direct reading PH meter. Moreover, soil colour was identified for each soil samples using Munsell color chart.

The undisturbed soil samples were analyzed for bulk density and saturated hydraulic conductivity (K_s). The K_s measurements were made using both the constant and falling head perimeter methods in the laboratory (Figure 4.7b). The soil in the core is held in place with a fine nylon cloth, tied with a rubber band and soaked in water until saturated. The soaked soil is fitted with another cylinder of the same diameter but of 20 cm height at the top of the core to allow imposition of a hydraulic head. A large metallic box with perforated false bottom is filled with fine gravel (<2 cm). A fast filtration filter paper is place on the soil core. With the core placed on the gravel box, water is gently added to the core to give a hydraulic head in the extended cylinder. The water then flows through the soil and is collected in the box and drained off by plastic pipe tubing. The fall of the hydraulic head at the soil surface was measured as a function of time using a water manometer with a meter scale and Ks was then calculated.

For consistency, all soils were described using the guidelines for soil description by FAO (1990). With the coordinates for all sampling points known from GPS readings, the records were critically examined and put in ArcGIS database. Thiessen polygons were defined for around each of the points using the ArcGIS Thiessen polygon tool. These polygons define the area that is closest to each point relative to all other points and they are mathematically defined by the perpendicular bisectors of the lines between all points (Figure 4.8).

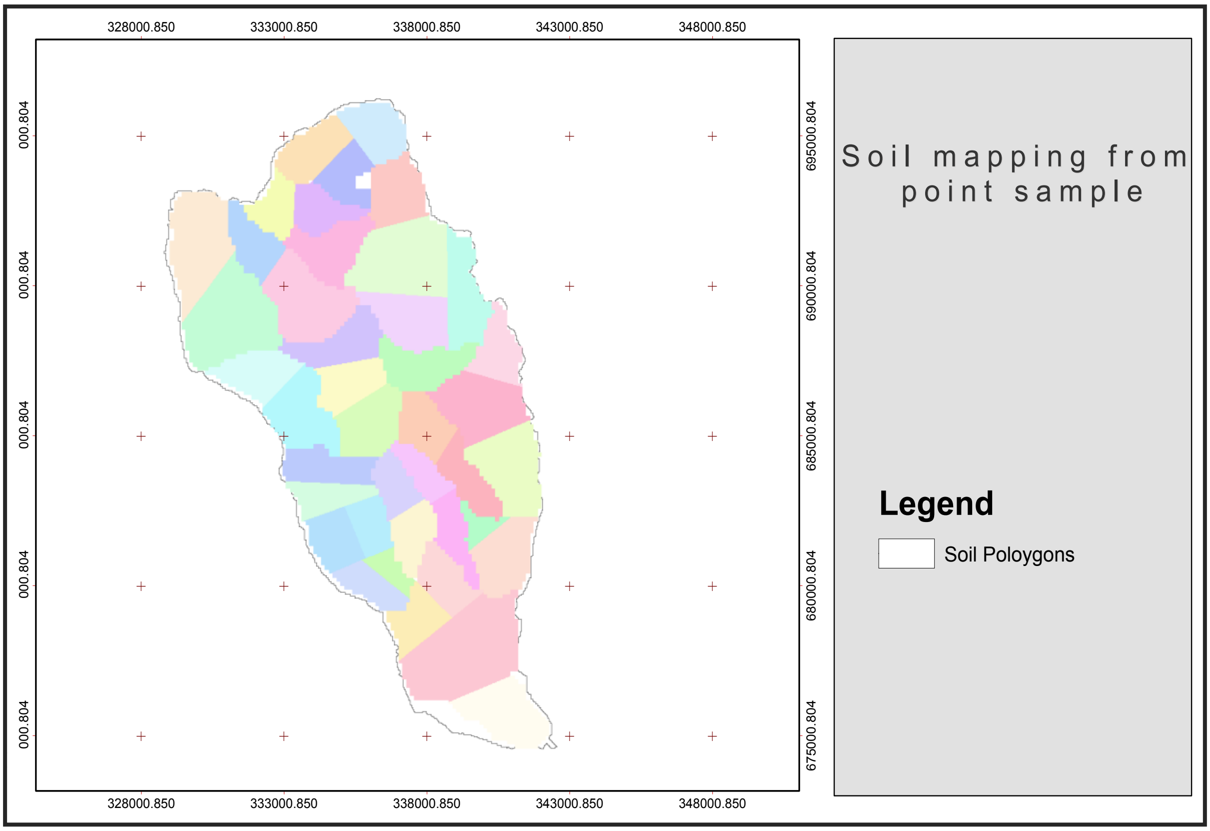


Figure 4.8 Soil polygons developed from point sampling at the study area

4.6.4 Streamflow Data and Groundwater Monitoring

River discharge is an important property that determines many of the physical, chemical and biological properties of a river system. The volume of water conveyed by a river affects water supply, stream ecosystems, power generation, and others. It is also important to know the timing of flow within and between seasons. In addition, it is used to indicate the present hydrologic conditions of a watershed and check methods for estimating present and future conditions. Therefore, to better manage water resources at the study area, it is essential to have a clear understanding of the characteristics of streamflow hydrology.

Daily discharge data of Hare River, for the period of 1980-2005, was acquired from Ministry of Water Resources that monitors the Rivers discharges in Ethiopia. Figure 4.9 presents the stream network of Hare River. This historic data reveal that the daily inflow to Hare River at the gauging station varied greatly during the dry and wet seasons. There is a surplus of water that flows to Lake Abaya during the wet season while in dry season water does not even suffice for current irrigation needs at downstream. Moreover, a new radar gauging station was established on Gina River to get an insight on the relative contribution of Gina River.

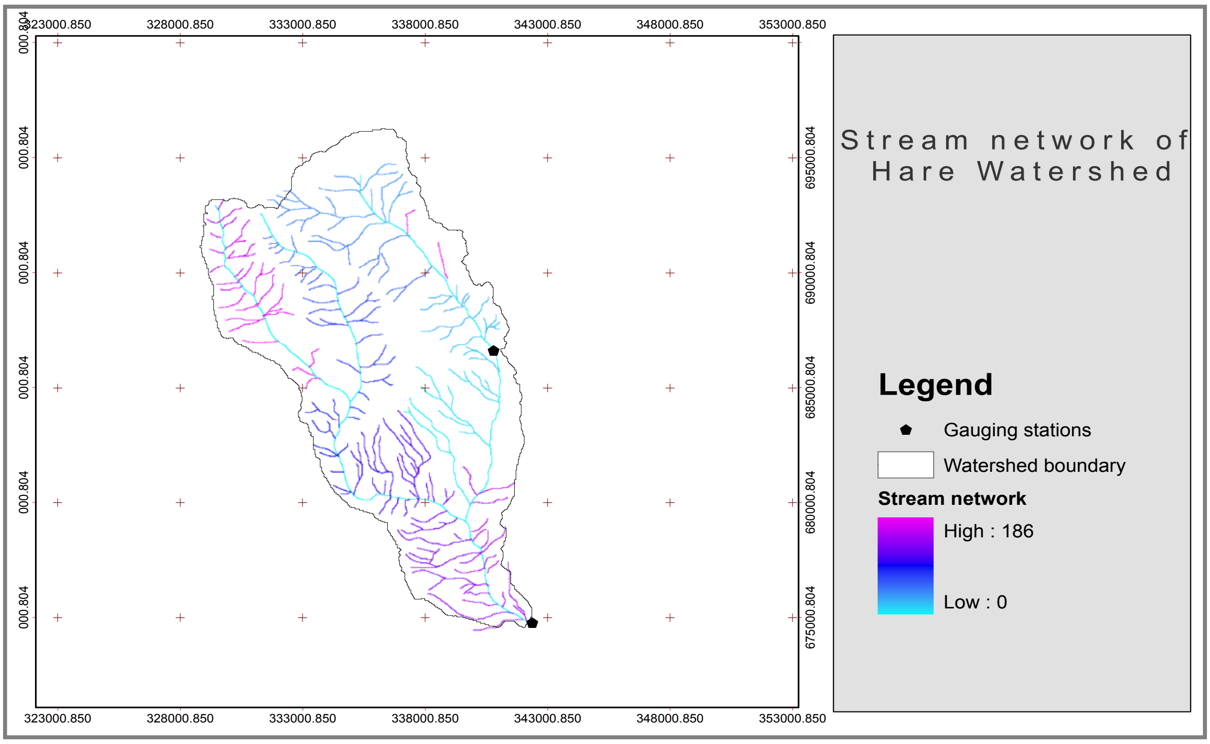


Figure 4.9 Stream network of Hare River

There was no data recoding at the watershed concerning groundwater resources prior to this research. This research therefore had to rely heavily on field measurements of hand-dug wells within the study period. Groundwater levels naturally fluctuate in response to seasonal and long-term variations in rainfall, recharge, and groundwater discharge. Periodic measurement of well-water levels is the only practical means of evaluating these changes. Weekly wells monitoring was carried out to quantify seasonal groundwater level fluctuation and to improve understanding of the hydro-geological conditions. Practically, due to the recent introduction of apple and other cash crops in the watershed, there is a rapid development of groundwater resources and therefore, groundwater is becoming an important source of irrigation water.

During the first visit of the study area in December 2005, hand dug wells suitable for groundwater level measurements were identified in the watershed, and their exact position and elevation was determined using GPS. Manual groundwater level measurements were taken at least once a week. In total, 27 hand dug wells were monitored between December 2005 and October 2007. Figure 4.10 presents the location of the wells at the three sampling sites which are naturally only sites where wells found throughout the watershed.

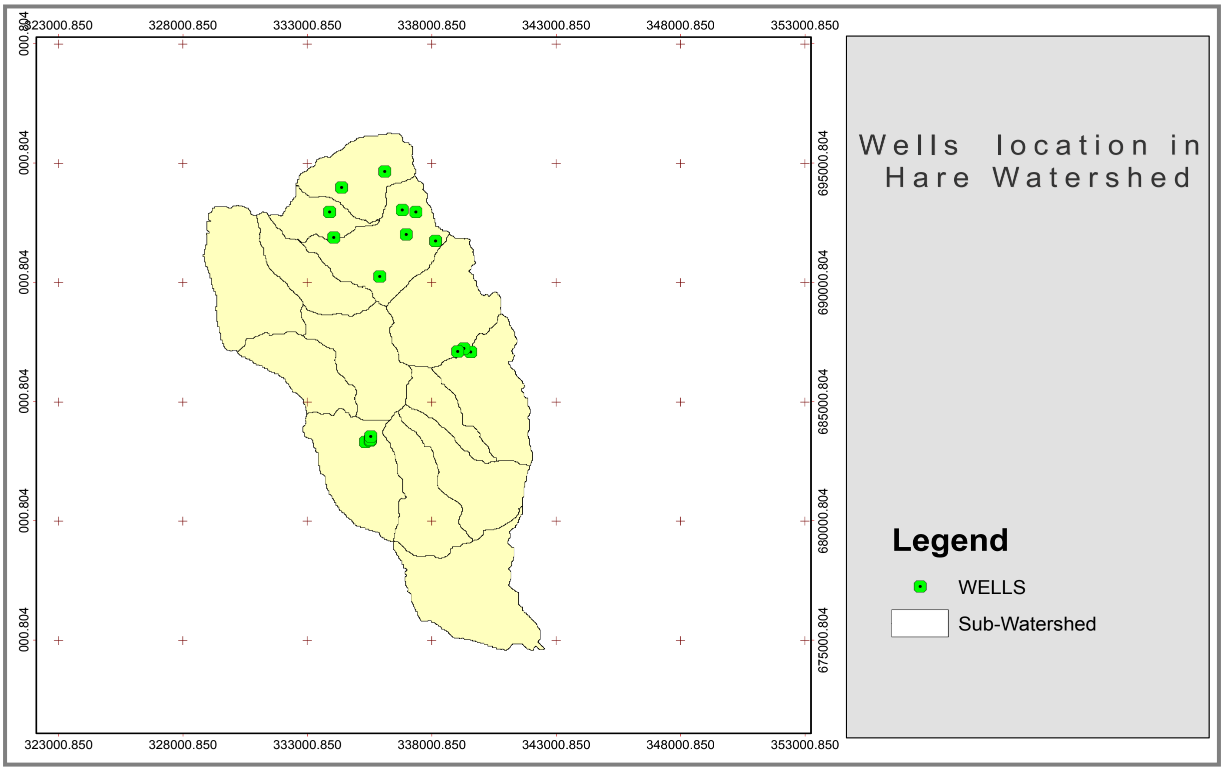


Figure 4.10 Location of wells assessed during the study

The spatial distribution of hand dug wells (Figure 4.10) shows that all groundwater production is located in the upper and middle reach part of the watershed in the Gina river system.

4.6.5 Watershed Characterization and Delineation

Delineation of watersheds from Digital Elevation Model (DEM) data has become standardized on the eight-direction pour point model. Each cell is connected to one of its eight neighbouring cells according to the direction of steepest descent. The most commonly used method of acquiring elevation data is digitizing contour maps and transforming them into a raster format using interpolation techniques. A digital contour was processed and interpolated to derive DEM of the study area. The DEM was used to delineate the topographic characterisation of the watershed and determine the hydrological parameters of the watershed such as slope, flow accumulation and direction, and stream network.

Both SWAT2005 and HSPF use similar approach in delineating a watershed. Watershed boundaries and sub-watersheds were delineated by overlaying the DEM, soil (Figure 4.8), stream network (Figure 4.9) slope (Figure 4.11) and land use and land cover maps (Figure 3.2).

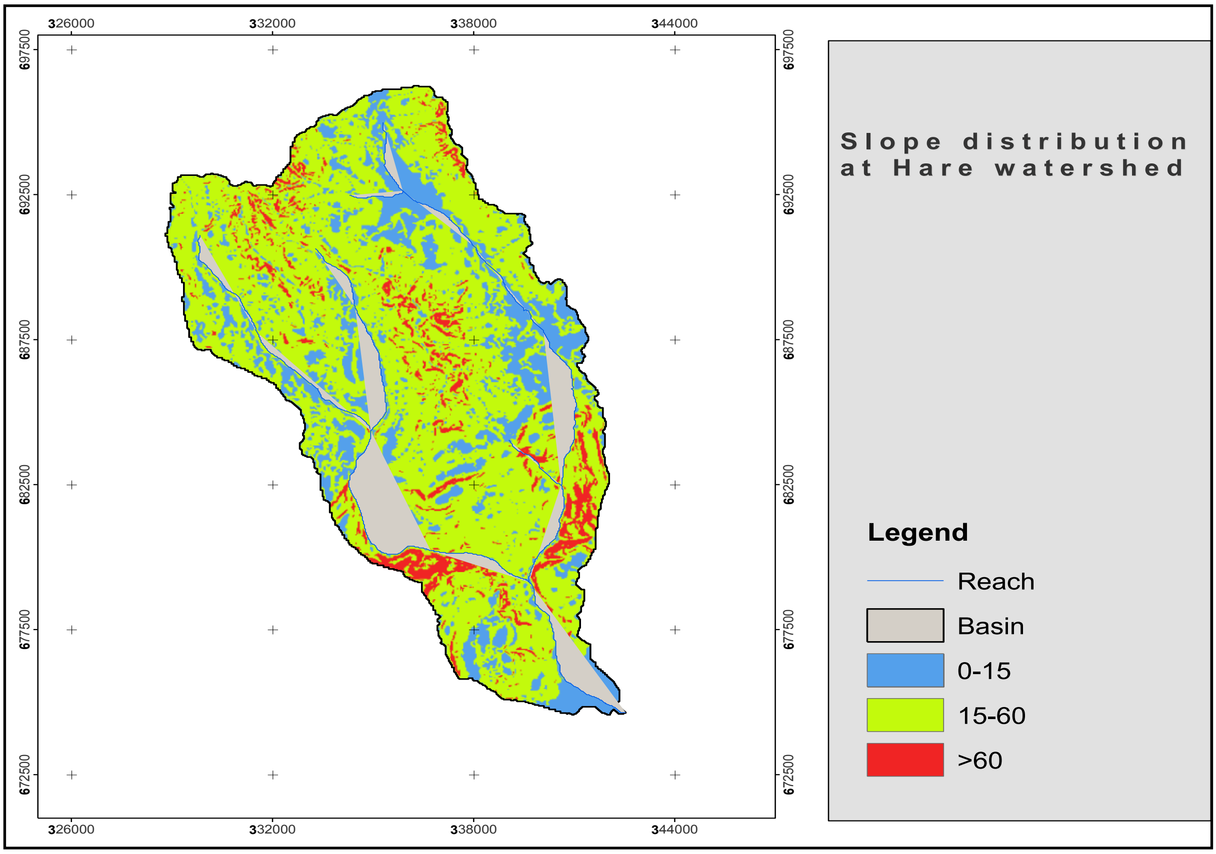


Figure 4.11 Slope distributions at Hare watershed

Using SWAT2005 Hare watershed was divided into 14 sub-watersheds and 163 HRUs that are determined by unique intersections (overlaying) of the land use and land cover, slope and soils within the watershed. This process enables to capture the heterogeneity of the physical properties.

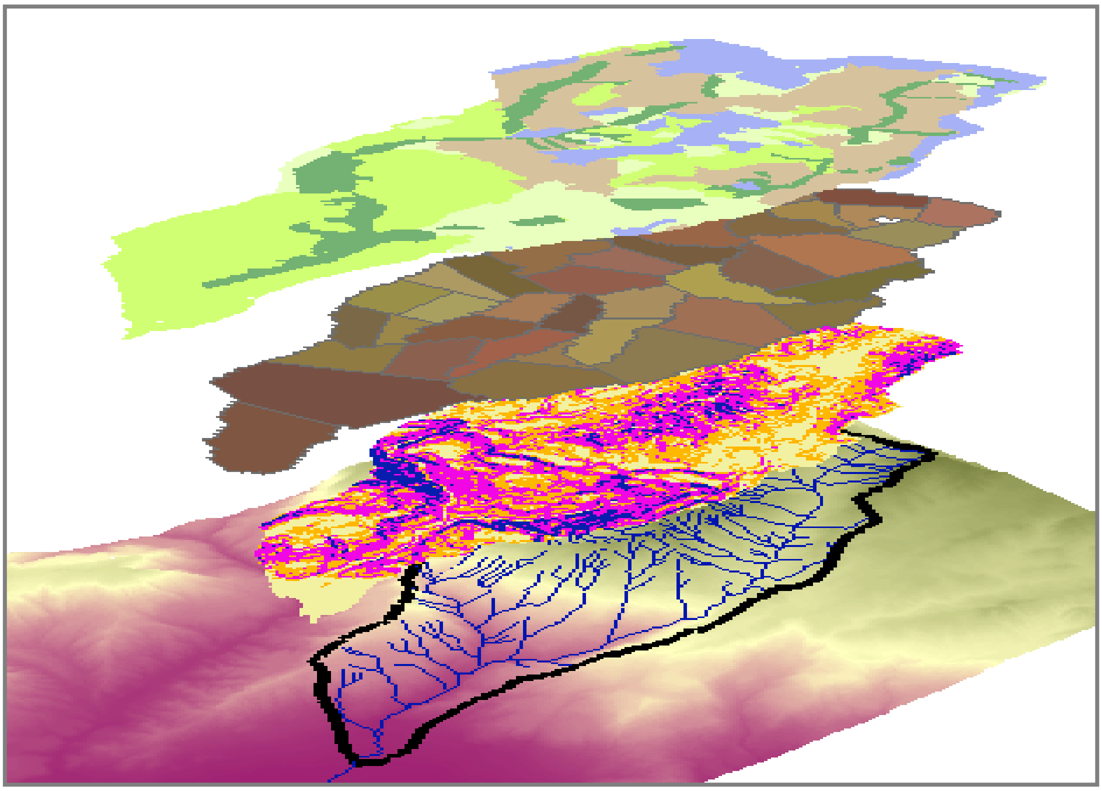
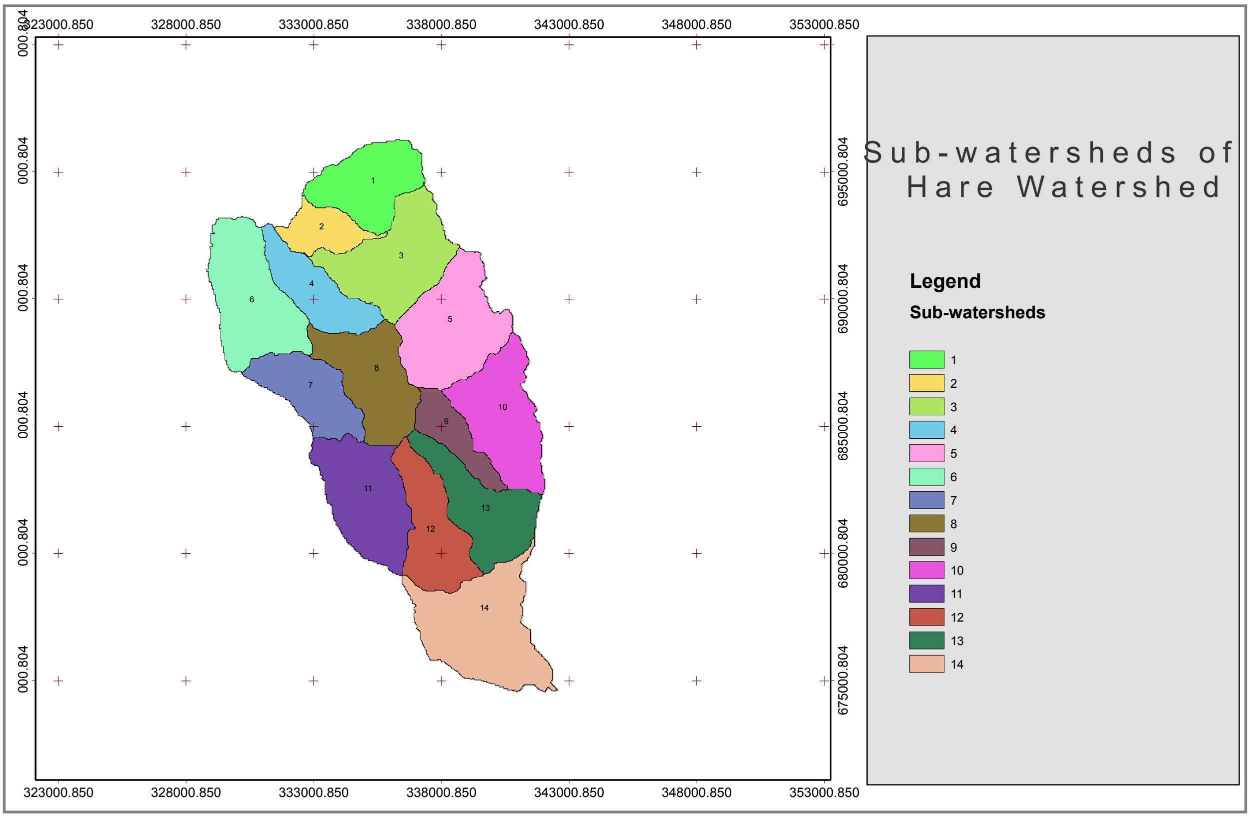
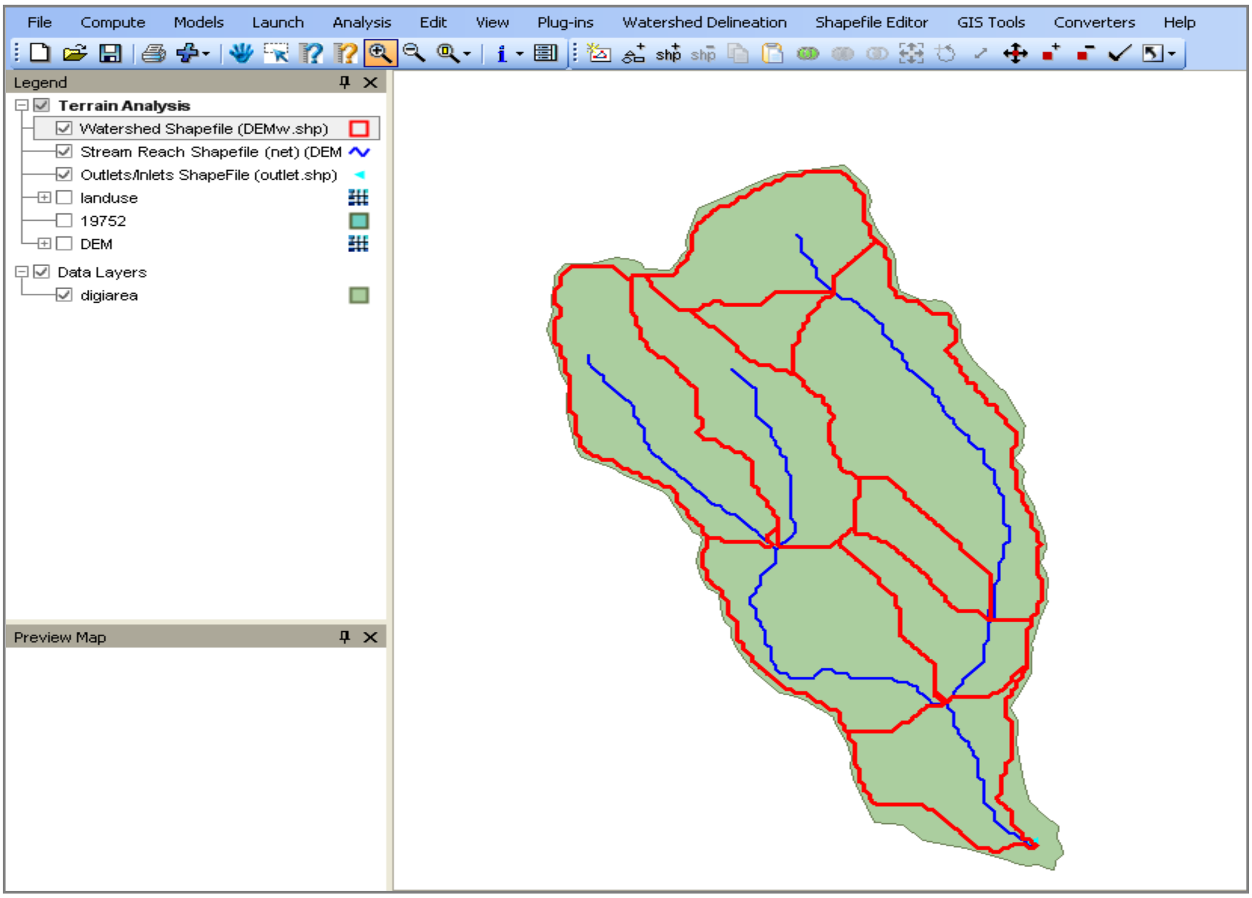


Figure 4.12 Overlaying the DEM, stream network, slope, soil and land cover maps

The 14 sub-watersheds delineated are presented in Figure 4.13. The HRUs are the spatial level at which the model computes the effect of management practices. Similarly, under the BASINS framework for HSPF model, Hare watershed was segmented into 10, approximately homogenous, sub-watersheds (Figure 4.14), so that lumped parameters could be assigned to each segment to represent its characteristics. For the segmentation, the topographical characteristics (e.g. elevation and slope) as well as land use and land cover was taken into account. In addition the discretization used for HSPF Model is in accordance with SWAT2005 Model discretization of the study area into hydrological homogeneous sub-watershed.



Figures 4.13 Sub-watersheds delineated for the study area using SWAT2005



Figures 4.14 Sub-watersheds delineated for the study area using BASIN for HSPF model

4.7 Preliminary Analysis of Models Input Data

4.7.1 Rainfall data analysis

In rainfall data analysis, it is important to identify whether the rainfall stations in or around a watershed are regionally exhibiting similar characteristics that will help for further analysis like filling missing values, develop rainfall-elevation relationships and runoff correlation. Abel (2005) compared the monthly distribution of rainfall at five stations near to Hare watershed and showed that all station exhibit a bimodal rainfall. Accordingly, peaked bimodal patterns are observed in the periods between March to June and August to November.

As outlined in Chapter 2 due to the high difference in elevation between the upper and lower parts of the watershed, orographic rainfall is considered to be a significant phenomenon at the study area. Accordingly, annual rainfall data of 15 weather stations (Table 4.2) was used to establish an elevation-precipitation relationship at the study area. Figure 4.15 illustrates a polynomial fit between elevation and rainfall based on annual average rainfall data of the nearby rainfall stations.

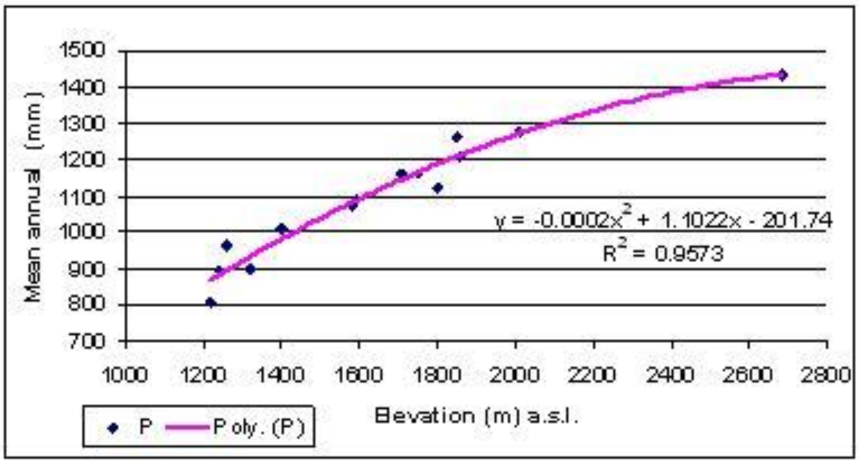


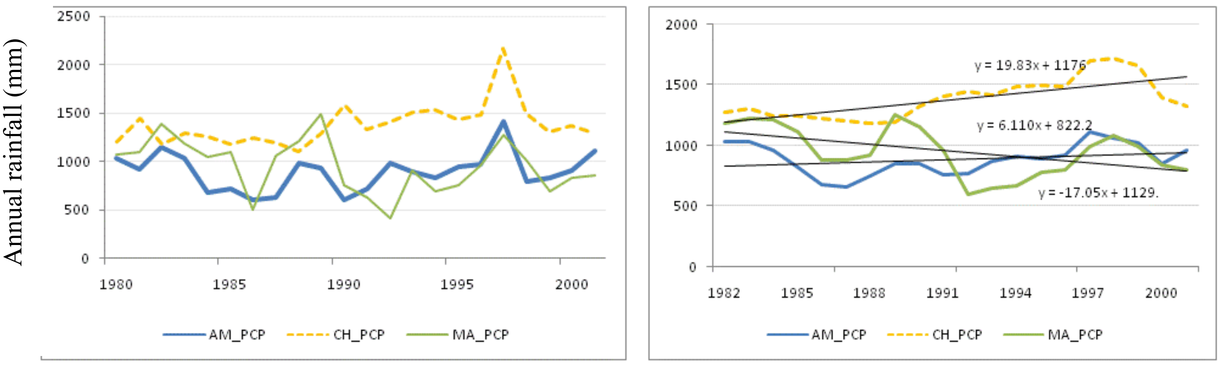
Figure 4.15 Elevation–rainfall relationships of meteorological station around Hare watershed

As illustrated in the Figure, a Pearson coefficient of determination (r^2) of 0.96 (n=15, $\alpha <$ 0.001) was observed. A similar result was reported (Krause, et al., 2004), which however indicated an increase trend until 2000 m a.s.l. and above that altitude significant relationship between elevation and rainfall is lacking. However, Figure 4.14 shows an increase trend in rainfall with increase in elevation. Moreover, Thiemann and Foerch (2005) developed an empirical relation between precipitation and elevation for Bilate river watershed with a similar trend. Based on the above result, the SWAT2005 elevation band tool was utilized to account the effect elevation on rainfall and consequently 10 elevation bands were defined in each sub-watershed. Rainfall is calculated for each band as a function of the respective lapse rate and the difference between the gage elevation and the average elevation specified for the band. This is computed by the following equation:

$$R_b = R_d + (EL_b - EL_g)\frac{R_l}{1000} \quad when\ R_d > 0.01 \tag{4.10}$$

Where R_b is the rainfall falling in the elevation band (mm), R_d is the rainfall recorded at the gage (mm), EL_b is the mean elevation in the elevation band (m), EL_g is the elevation at the recording gage (m), R_l is the rainfall lapse rate (mm/km), and 1000 is a factor to convert meters to km.

The climate of the study area then determined by the long-term average, frequency and extremes of temperature and rainfall data. For the reason that the sporadic nature of rainfall, with some days receiving no precipitation and other days receive abundant amount of precipitation, the analysis is mainly focused on precipitation data to get a detail insight in terms of its distribution and variability at the three important nearby stations, Arba Minch, Chencha and Mirab Abaya. Figure 4.16 below present the annual precipitation distribution and 3-years moving average of the three stations over the year 1980-2004.



(a) (b)

Figure 4.16 Annual precipitations distribution (a) and 3-years moving average (b)

As it can be depicted from the Figure 4.15a, Chencha station has received maximum over the past four decades than Arba Minch and Mirab Abaya. Moreover, the linear trend fitted to 3-year moving averages of the annual rainfall indicates that annual rainfall has increased at Chencha station (19.8 mm per annum) and slightly at Arba Minch station (6.1 mm per annum) where as it decreased at Mirab Abaya Station at 17.1 mm per annum.

Although, in Ethiopia, seasons are characterized as Bega (October to January), Belg (February to May) and Kiremt (June to September), the classification doesn't encompass the southern and south eastern lowlands of the country, which have a bimodal rainfall with rainfall periods from March to May (MAM) and from September to October (NMSA, 1996). Accordingly, wet spells and dry spell analysis were performed for the months March to May (MAM) and December to February (DJF) respectively.

Wet spells, defined as the number of consecutive days with at least 1 mm of rainfall, are an inherent property of climate, and depending upon their durations and the rainfall associated with them, they can have distinct advantages as well as disadvantages. For instance, in agriculture, wet spells of relatively short duration, typically not exceeding 3 days and with light to moderate rainfall, can be very conducive to crop growth. However, if the spells are long, crop damage can easily set forth as a result of water logging in the soil or even flooding. In this research, individual station daily rainfall records were accordingly examined for occurrences of wet-spells.

The aim of studying the wet and dry spells in this research is to get an overview of the most relevant patterns of wet and dry spell lengths (and durations) in the Hare watershed in order to obtain their spatial and temporal description in relation to water availability. Moreover, wet and dry spells provides information for running the future water balances and will improve farmer's ability to accomplish cultivation at the right time. Therefore, historical occurrences of wet spells at Arba Minch and Chencha stations in the main rainy season are examined for the period 1980 to 2004.

Table 4.3 illustrates the statistical description of monthly rainfall at Arba Minch (AM) and Chencha (CH) stations. The table indicates the mean, variance, Inter Quartile range (IQR), Autocorrelation Function (ACF) and wet-days percentage of each month.

Table 4.3 Statistical description of rainfall at Arba Minch and Chencha stations

	Mean		*Variance*		*IQR*		*ACF*	
Month	AM	CH	AM	CH	AM	CH	AM	CH
January	6.14	8.18	45.77	56.85	7	6.15	0.26	0.21
February	7.01	9.07	97.66	65.16	6.93	7.18	0.17	0.40
March	7.92	7.24	47.09	29.48	5.98	5.10	0.22	0.32
April	11.47	9.83	103.69	68.67	10.7	6.80	0.13	0.39
May	12.07	10.1	112.07	92.37	12.05	6.98	0.04	0.60
June	9.59	9.82	83.89	41.53	8.83	4.80	0.09	0.35
July	8.5	8.94	65.6	84.86	6.68	6.40	0.13	0.28
August	8.88	8.76	100.36	49.82	7.35	7.10	0.26	0.22
September	8.17	9.9	69.04	44.72	6.33	7.60	0.09	0.32
October	10.02	11.99	102.86	101.06	11.4	8.95	0.18	0.29
November	8.13	9.27	78.17	60.44	9.35	6.23	0.3	0.35
December	7.6	7.28	92.69	42.68	8.93	4.83	0.33	0.31
DJF	6.91	8.18	81.96	55.94	7.8	6.10	0.27	0.32
MAM	10.48	9.05	96.92	58.47	9.85	6.30	0.13	0.45
JJA	8.99	9.17	83.67	60.33	8.1	6.60	0.16	0.28
SON	8.77	10.38	83.36	69.17	8.9	7.60	0.19	0.32
Annual	8.79	9.2	89.09	61.41	9.1	6.70	0.19	0.35

As indicated in the table, variability of rainfall during the months of April, May, August and October are high. The IQR, which is the difference between the 25^{th} and 75^{th} percentiles indicate that the disparity between those percentiles is almost similar for all months and seasons at Chencha station while similar for most of the months except that of April, May and October at Arba Minch stations. These three months where high rainfall is recorded. Similarly, the ACF that is a measure of the linear association between successive rainfall days indicate that the successive days are unrelated and thus have values near to zero. Unlike temperature, in which case successive days tend to be positively auto-correlated, successive precipitation days are uncorrelated. However, successive days at Chencha station are better correlated than Arba Minch station.

Comparison of mean monthly wet percentage at Arba Minch and Chencha stations is given in Figure 4.17.

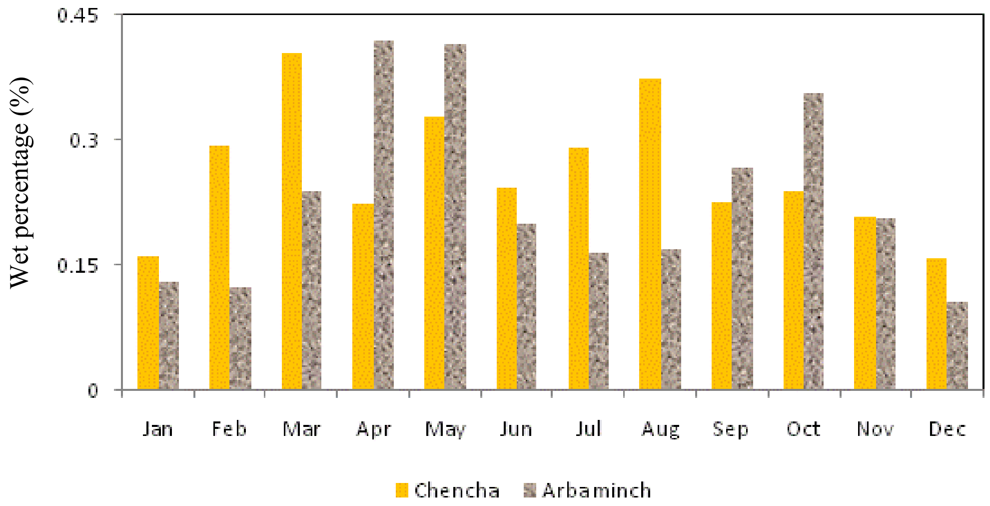


Figure 4.17 Mean monthly wet percentages at Arba Minch and Chencha Stations

As it can be clearly seen from the figure, Arba Minch station has got more wet-days in April, May, and October while Chencha has more wet percentage during the rest months. Moreover, the months November to February have minimum wet-percentage days indicating that they are dry months. Furthermore, Figure 4.18 provides mean dry spell for the months DJF during which supplemental irrigation water is required for crop production.

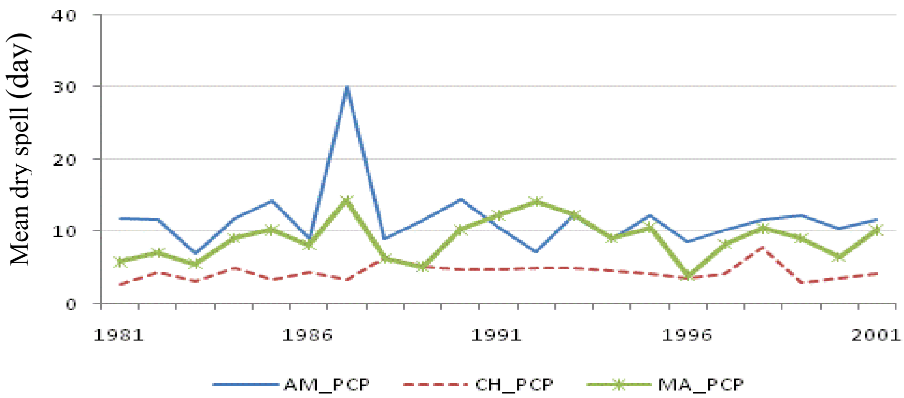


Figure 4.18 Mean dry spell during the months of DJF

Dry-days occurs more often at Arba Minch and Mirab Abaya stations while at Chencha station dry-spell is generally less than 7 days. Off course, some of these values are still not conducive for crop production where most crops are sensitivity when the dry spell is greater than 3 days during their critical growing stage.

Furthermore, in order to account for water availability during the those seasons, the Standard Precipitation Index (SPI) (McKee et al. 1993) is used to categorize observed rainfall as standard departure with respect to a rainfall probability function and used to monitor wet spells (positive SPI) or dry spells (negative SPI) over the period 1980-2004. Figure 4.19 below provides how rainfall for a monthly base at Arba Minch and Chencha stations compared with the long term precipitation record of the same site of the same duration.

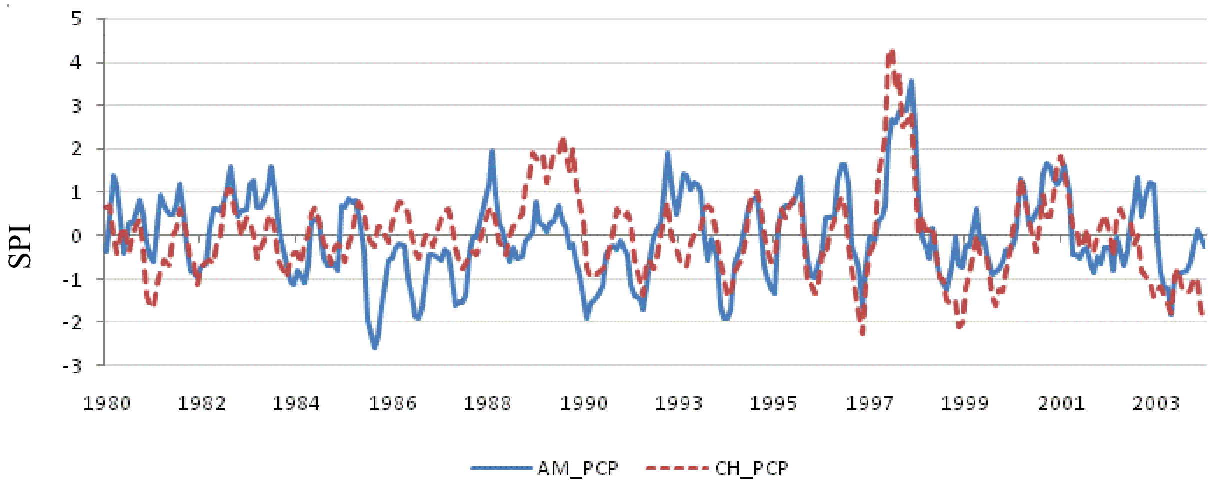


Figure 4.19 Standard Precipitation Index at Arba Minch and Chencha stations

The SPI is derived by first calculating the monthly sums of the data, and then calculating a moving average of these monthly sums (smoothing) across three. The smoothed data are then normalized by subtracting the mean of all the data in the fit range and dividing by the standard deviation of the smoothed data for each month. The SPI value is determined by the probability of a given incremental rainfall anomaly occurring during the period of the analysis based on a gamma probability density function fit to the time series of monthly rainfall. For example, a SPI value of -1.5 presents a dry anomaly that occurred with a probability of 6.7% or less (McKee et al. 1993), and thus falls into the dry-spell category in the SPI ranking system.

As it is illustrated in Figure 4.18 for the 24-year analysis period Arba Minch station has much dry spell periods especially during the period 1985 to 1995 while Chencha has only four years dry spell (1980, 1997, 1999 and 2003). Generally, the analysis of the trends of the mean length of the wet spells over the 1980–2004 period reveal a positive trend during the months MAM and negative trend during the months DJF.

4.7.2 Analysis of Soil Data at Hare Watershed

Though the major aim of soil data collection was to prepare the input data for the SWAT2005 model, analyses were performed to get more information on the distribution of soil properties and to identify the variation in soil types. Therefore, in this section the spatial distribution of the different soil types and the relationships between soil properties among the soil layers and sampling sites at the study area. Accordingly, the soils were classified into different textural classes using the textural triangle using the computer program for soil textural classification developed by Gerikis and Baer (1999) that uses percent sand and clay (Figure 4.20a) based on the USDA method of classification. Sample of soil texture determination procedure is provided in Appendix 4.5.

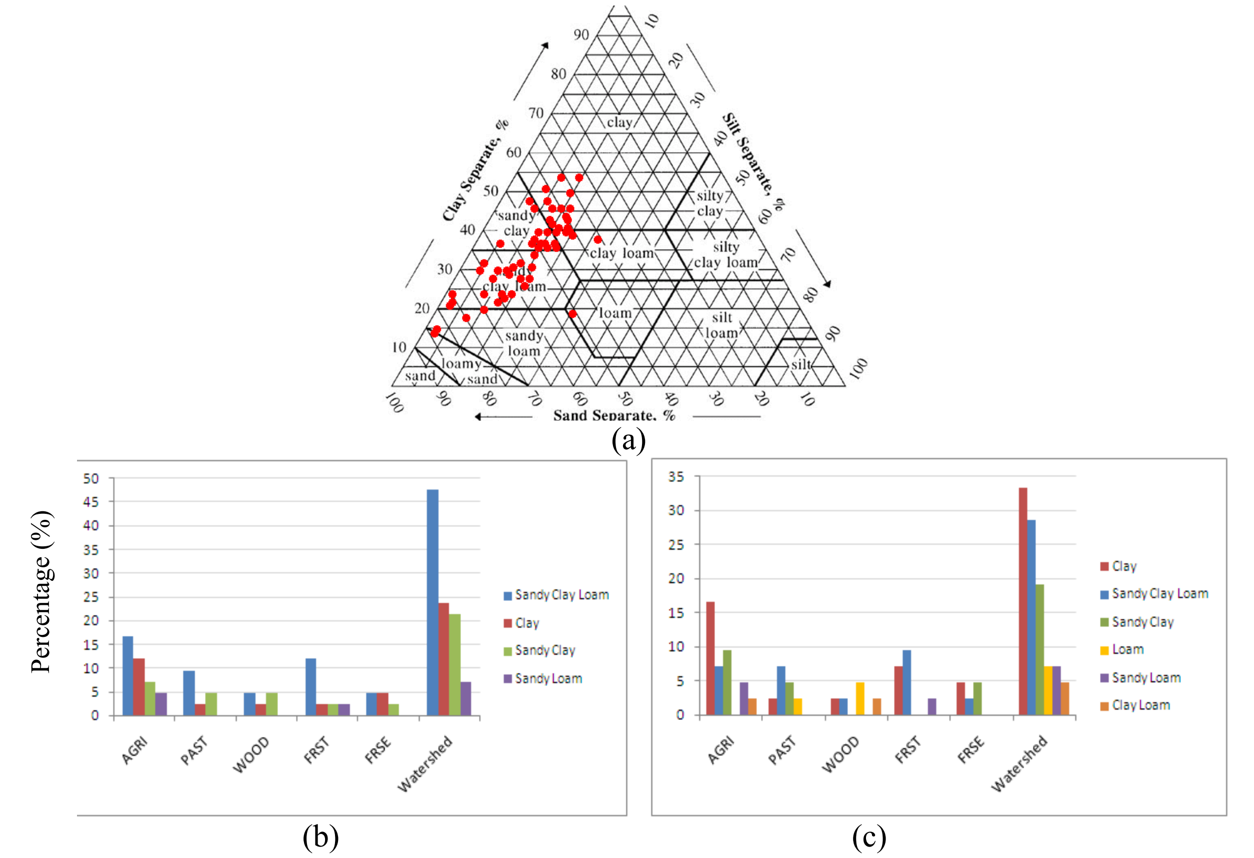


Figure.4.20 Soil texture distribution of the watershed (a), topsoil (b) and subsoil (c)

As indicated in Figure 4.20, the soil texture is dominated by sandy clay loam, clay, sandy clay and sandy loam in the topsoil and clay, sandy clay loam, sandy clay, sandy loam, loam and clay loam in the sub soil in decreasing order of distribution. This shows that the texture in the subsoil is generally heavier than that in the topsoil particularly in the agricultural lands. The range for sand, silt and clay content for both topsoil and subsoil is wide with a sharp increase in clay content from the topsoil to the subsoil, which may be due to soil translocation from the topsoil to the subsoil. In general, the watershed has a mean texture of sandy clay loam in the topsoil and sandy clay in the subsoil.

Presented in Table 4.4 are the descriptive statistics of soil properties at the study area. It provides information on the minimum, maximum, mean and Coefficient of Variation (CV) values for the top and sub soils physical and chemical parameters.

Table 4.4 Descriptive statistics of soil properties in the topsoil and subsoil

Parameter	*Soil level*	*Min.*	*Max.*	*Mean*	*CV (%)*
CLAY (%)	Topsoil	9.00	45.00	30.45	28.68
	subsoil	11.00	56.00	37.16	33.12
SILT (%)	Topsoil	7.00	22.00	17.84	21.11
	subsoil	5.00	33.00	15.87	37.50
SAND (%)	Topsoil	36.00	84.00	51.71	20.95
	subsoil	27.00	78.00	46.97	30.14
SOL_BD (g/cm^3)	Topsoil	1.26	1.54	1.35	4.73
	subsoil	1.25	1.53	1.36	6.20
SOL_AWC(mm/mm)	Topsoil	0.06	0.13	0.10	65.90
	subsoil	0.06	0.13	0.10	14.10
SOL_K (mm/hr)	Topsoil	2.00	24.23	4.14	89.75
	subsoil	1.04	20.63	5.30	93.04
SOL_OC ((% wt)	Topsoil	5.03	15.09	9.33	28.14
	subsoil	2.90	10.42	6.31	32.19
PH	Topsoil	4.01	6.37	5.50	10.21
	subsoil	4.47	5.93	5.43	6.95
SOL_EC (µs/cm)	Topsoil	18.00	135.00	62.53	45.67
	subsoil	21.00	88.00	41.21	51.89
Ca++ (meq/100g)	Topsoil	5.00	50.00	18.13	63.61
	subsoil	5.00	35.00	13.21	64.02
Mg++ (meq/100g)	Topsoil	1.22	26.73	6.25	107.98
	subsoil	1.22	8.51	3.74	61.47
Na+ (meq/100g)	Topsoil	0.43	11.17	2.42	123.81
	subsoil	0.22	3.44	1.27	72.40
K+ (meq/100g)	Topsoil	0.17	11.00	3.67	103.84
	subsoil	0.37	7.41	1.46	136.26
CEC (meq/100g)	Topsoil	7.11	66.90	29.74	56.91
	subsoil	8.53	38.92	20.47	43.12

As compared to sand soil, clay soils have high CV at topsoil (28.7%) while silt soils have high CV at the subsoil (37.5%) that could be due to the different land use practices at the watershed. Similarly, there is high CV among the values of all cations that could be again resulted from the same reason. The hydraulic conductivity and soil organic carbon have high CV at the top soil (93.04% & 28.14 %) and subsoil (89.8% & 32.19%) respectively. On the other hand, CV of bulk density and soil PH is small as the range varies between 1.25-1.54 for bulk density and 4.0-6.37 for soil PH. The comparison of the relationship between soil parameters among the different land use and land covers is provided in Table 4.5.

Table 4.5 Soil parameters distribution among the land use and land cover classes

	AGRI	*PAST*	*FRTS*	*WOOD*	*RIVB*
CLAY (%)	36.17	34.41	38.34	36.00	36.50
SILT (%)	14.17	11.48	13.39	14.44	15.00
SAND (%)	49.67	54.11	48.27	49.56	48.50
SOL_BD (g/cm^3)	1.36	1.36	1.33	1.35	1.34
SOL_AWC (mm/mm)	0.15	0.17	0.17	0.18	0.14
SOL_CBN (% wt)	6.70	8.11	13.28	6.18	8.68
PH	5.38	5.71	5.34	5.65	5.59
EC (µs/cm)	53.82	54.71	45.50	58.00	34.00
CEC (meq/100gm)	22.57	26.62	46.99	26.38	43.56

AGRI=Agricultural lands and settlements, PAST= Pasture lands, FRTS= Forest lands, WOOD= Woodlands and RIVB= Riverine trees and Bamboo

As evidenced in the table, average of clay and silt distribution is similar in all land uses while sand soil percentage is a bit higher in pasture lands. On the other hand, soil organic matter is higher (13.28 %) at land uses with forest cover than farming lands (6.7 %). It seems that the conversion of forest lands to other land uses has decreased the organic matter content in the soils. Similarly, the cation exchange capacity of the soil ranges from 22.52 to 47.0 meq per 100g of soil, the higher value being at forest lands and lowest value at land use under farming system. The variation of soil PH at the study area is small both among the different land uses and ranges from 4.01 (very strong acid) to 6.37 (slightly acidic).

On the other hand, different soil pattern observed when analysis is made among sub-watersheds. For instance sub-watershed 14 (11 % of the watershed), mainly forested area is dominated by a single soil type (57 %) with sandy clay loam soil texture. On the other hand, sub-watershed 6 (9.2 % of the watershed), dominated by agricultural land (47 %), contains two major soil types with sandy loam texture (42.6 %) and clay texture (51.3 %).

In order to determine the magnitude of association, direction of association, and the statistical significance level between different pairs of variables, correlation analysis was performed on the soil data. Pearson's r correlation matrix was constructed after a min-max transformation with the range of zero-one (0-1) for normalized data. This transformation is a method of standardization that gives data with a minimum value of zero and a maximum value of one. Min-max transformation was used to put all data on a common scale. The following min-max (0-1) function was used to transform the data:

$$Y' = \left(\frac{Y - \min 1}{\max 1 - \min 1} \right) (\max 2 - \min 2) + \min 2 \tag{4.11}$$

Where Y is the original value, Y´ is the new value, min1 is the original minimum value, and max1 is the original maximum value. Also, min 2 = 0 and max 2 = 1 are the new minimum and maximum values, respectively.

The Pearson's correlation among the normalized soil data is summarized in Appendix 4.6. As indicated in the Appendix there is significant cross correlations among most of the soil parameters at a significance level 0.05. The clay content has a positive correlation with soil available water, soil bulk density, soil organic carbon and cation exchange capacity and a negative correlation for other soil properties. On the other hand, hydraulic conductivity has positive correlation with sand and CEC but negative correlations for the other soil properties. Significant correlations are also observed amongst other parameters as indicated in the table.

4.7.3 Analysis of Streamflow and Groundwater Levels

Due to the reason that Hare watershed has short response, daily maximum, mean and minimum flows are used (Figure 4.21) to plot the hydrographs that may conceal important fluctuations and variations. As it can be depicted from Figure 4.21 (a), there are high flows during the months May and end of October that corresponds the two rainy periods occurring at the watershed.

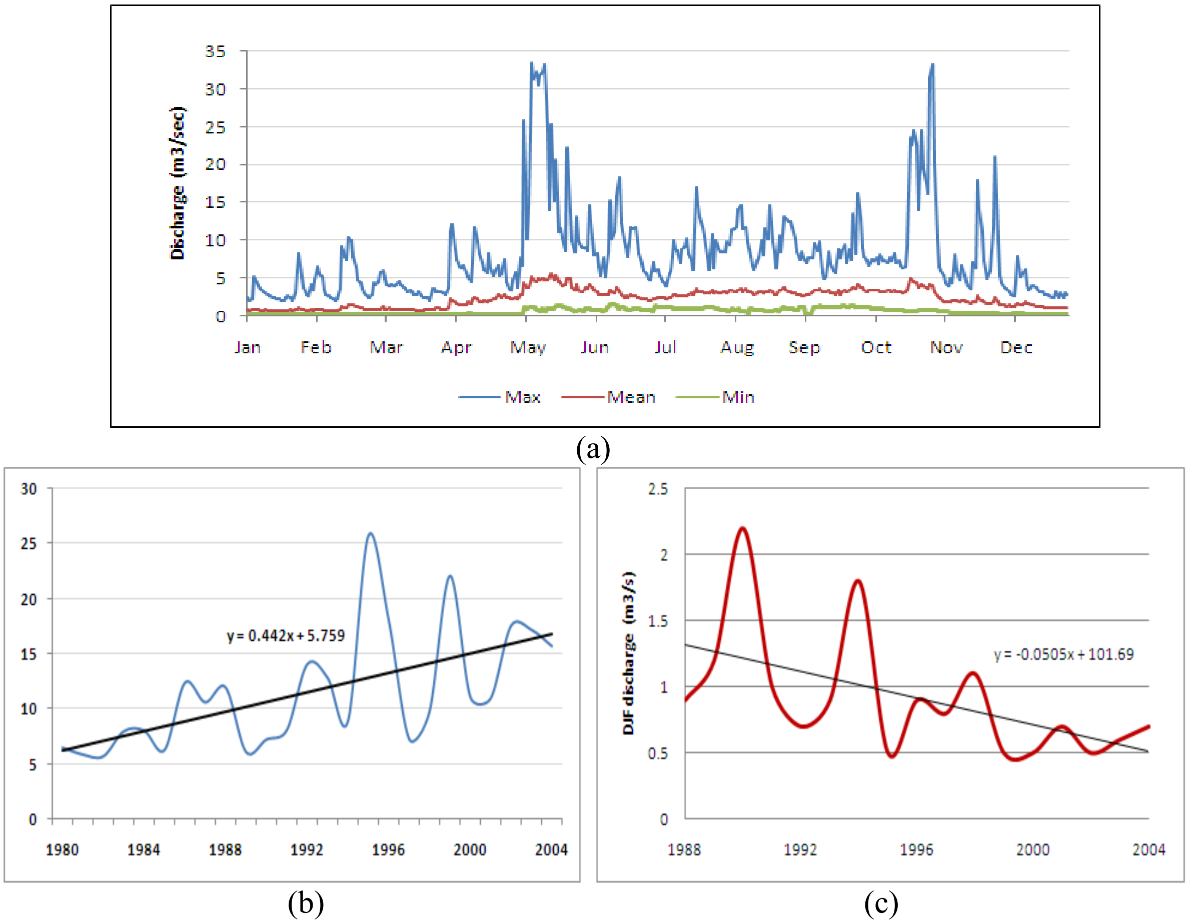


Figure 4.21 Maximum, minimum and average daily flows (a), trends in seasonal maximum flow (MAM) (b) and minimum flow (DJF) (c) of Hare River

Despite an increase in rainfall in the upper part of the watershed, the trends in seasonal flows in Figure 4.21 (b) and (c) clearly indicates that there is an increase in maximum flows during the rainy seasons at a rate of 0.442 m^3/sec per annum and there was a decrease in low flows during the dry season at a rate of 0.051 m3/sec per year.

Groundwater levels at the study area illustrated that there is fluctuation in response to seasonal and long-term variations in rainfall, recharge, and natural groundwater discharge. The results of the periodic wells-water levels measurement undertaken at 32 hand-dug wells in four sub-watersheds (1, 3, 5 and 7) for the period of April, 2006- October, 2007 are provided in Figure 4.22. The figures are arranged taking in to account their geographical location. The first two are located in the middle of the watershed, sub-watersheds 5 (Godeye) and 6 (Shama), and the next two are located in the upper part of the watershed, sub-watersheds 3 (Mesho) and 1 (Yeweyra).

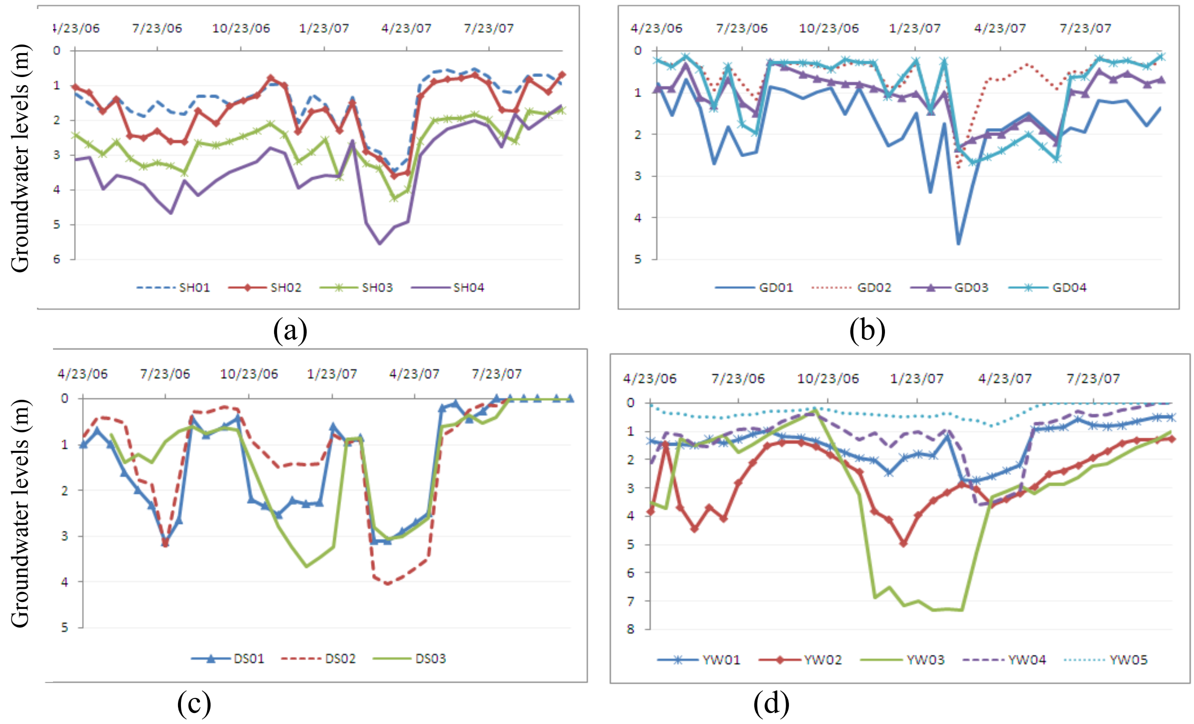


Figure 4.22 Groundwater level fluctuations at Sub-watersheds 5 (a), 6(b), (3) and (1)

There is quite a large variation in the response of the monitored wells to rainfall even on the comparatively small scale of the study area. Some wells respond quickly to the onset of the rainy season, and their water level starts dropping shortly after the last rains. However, other wells respond much more slowly with a more delay time. In sub-watershed 5 (a) and 6 (b), the responses of the wells to rainfall have more or less similar trends in which their lowest water levels are during February and March, just before the beginning of the major rainy season. However, at sub-watersheds 3 (c) and 1(d) the ground water levels start to drop immediately after the second rainy season (end of October).

In sub-watershed 1, the variation of ground water level at wells coded YW03 and YW05 is very different. The fluctuation of the water level at YW03, which is situated relatively on a plane surface, is very small for the whole observed period. The reason other than its location could be the availability of a year round spring at a nearby distance. On the other hand, YW05 which is located at highest elevation than all the observed wells, respond very quickly and its water level drops dramatically after October and it maintains that level until the major rainy season commences.

4.8 Conclusions

Currently, with advances in computational power and the growing availability of spatial data, hydrological models are being attractive tools to analyze the functioning of hydrology, operation, social and economic processes, as well as others that can occur in a basin, with the objective of setting and evaluating management alternatives in water resources management. Specifically, for this research, hydrological modeling techniques are identified to be useful tools for investigating interactions among the various watershed components and hydrologic response analysis to LUCC and river basin management at various spatial scales. Moreover, the use of hydrological models has a paramount importance for integrated water resources management that improves resources management based on sound scientific principles.

The purposes of modeling and data availability are essential criteria for selecting a hydrological model to evaluate hydrological responses to land use and land cover and management practices to support integrated water resources management plans. For a simple hydrological problem, a simple conceptual model can be appropriate. However, with more complex water resources management problems where land use and climate change may need to be considered, more complex hydrological models should be used.

The choice of a model is not a simple task since each model has certain data requirements which are not always easy to obtain. Models are quite often specific to a particular problem and it is challenging to make a choice about a model that can serve different modelling purposes, as it is in case of this study. None of the available models can be thought of as ‘perfect’ since such a model does not exist. However, there are models which represent reality in more or less better ways.

Accordingly, based on a literature review and a set of model selection criteria, SWAT2005 and HSPF were selected for this research. The models provide the best possible options for modeling existing land–water linkages, impact analysis and future land use and climate change scenarios. These models are useful for long-term continuous simulations and assessments of hydrological changes and watershed management practices, especially agricultural practices. Moreover, the capabilities of the models to use GIS environment make the models sound for such application. Finally, these models can be potentially used in other watersheds with different sizes, and different climatic, hydrologic, and geologic conditions in developing countries like Ethiopia.

After collecting all appropriate data sets for SWAT2005 and HSPF, a preliminary analysis was made on rainfall, soil, streamflow and ground water in line with the objectives of this thesis. Initially, Hare watershed was divided in to 10 and 14 sub-watersheds using the BASINS platform for HSPF and SWAT2005 models respectively. A unique combination of land use and land cover, soil and slopes were used to divide each sub-watershed in to HRU while using SWAT2005. Accordingly, a total of 163 HRU were developed during the process. The preliminary analysis on rainfall illustrated that Arba Minch station has much dry spell periods especially during the period 1985 to 1995 while Chencha has only few years' dry spells. Moreover, the analysis of the trends of the mean length of the wet spells over the 1980–2004 period reveal a positive trend during the months MAM and negative trend during the months DJF.

On the other hand, analysis made on the soil parameters revealed that clay content has a positive correlation with soil available water, soil bulk density, soil organic carbon and cation exchange capacity and a negative correlation for other soil properties. Whereas, hydraulic conductivity found to have positive correlation with sand and CEC, while it has negative correlations for the other soil properties. Significant correlations are also observed amongst other soil parameters. In relation to groundwater, wells that are located at highest elevation respond very quickly and their water level drop dramatically after October and maintain that level until the major rainy season commences. In contrast, the variations of ground water level at wells that are situated relatively on a plane surface are very small for the whole observed period. The reason other than its location could be the availability of a year round spring at a nearby distance.

CHAPTER 5

Hydrological Model Performances, Sensitivity and Uncertainty Analysis

5.1 Introduction

The ability of a watershed model to sufficiently predict streamflow for a specific application is evaluated through sensitivity analysis, calibration, validation and uncertainty analysis. Sensitivity is measured as the response of an output variable to a change in an input parameter, with the greater the change in output response corresponding to a greater sensitivity. It evaluates how different parameters influence a predicted output. Parameters identified in sensitivity analysis that influence predicted outputs are often used to calibrate a model (White and Chaubey, 2005; Van Griensven et.al. 2006).

Vandenberghe et al. (2001) also highlighted the complementarities of the sensitivity analysis and the parameter calibration. Sensitivity analysis is usually the first step towards model calibration because it answers several questions such as; (a) where data collection efforts should focus; (b) what degree of care should be taken for parameter estimation; and (c) the relative importance of various parameters. Therefore sensitivity analysis as an instrument for the assessment of the input parameters with respect to their impact on model output is useful not only for model development, but also for model validation and reduction of uncertainty. There are different methods available for carrying out sensitivity analyses and expressing their results (Beven, 2001; van Griensven et al., 2002; Van Griensven et al., 2006).

On the other hand, model calibration entails the modification of parameter values and comparison of predicted output of interest to measured data until a defined objective function is achieved (James and Burges, 1982). The objective function for model calibration generally consists of a statistical test, such as minimization of relative error, minimization of average error, or optimization of the Nash-Sutcliffe Coefficient (E_{NS}) (Santhi et al., 2001; Grizzetti et al., 2003). After achieving the objective function for calibration, validation of the model ensues. Validation procedures are similar to calibration procedures in that predicted and measured values are compared to determine if the objective function is met. However, a dataset of measured watershed response selected for validation preferably must be different than the one used for model calibration, and the model parameters are not adjusted during validation. Validation provides a test of whether the model was calibrated to a particular dataset or the system it is to represent.

Shirmohammadi et al. (2006) defined uncertainty as the estimated amount by which an observed or calculated value may depart from the true value. They discuss sources of uncertainty and list model algorithms, model calibration and validation data, input variability as key sources of uncertainty. Different authors elaborated that all model calibrations and subsequent predictions are subjected to uncertainty. This uncertainty arises from the fact that no model is a true reflection of the processes involved, that it is impossible to specify the initial and boundary conditions required by the model with complete accuracy, and that the observational data available for model calibration are not error-free (Beven, 2001).

Abbaspour (2007) pointed out that watershed models suffer from large model uncertainties that can be characterized as: (1) *Context*, i.e. at the boundaries of the system to be modeled that includes the external economic, environmental, political, social and technological circumstances that form the context of problem; (2) *Input uncertainty* in terms of external driving forces and system data that drive the model such as land use maps and climate data; (3) *Model structure uncertainty* is the conceptual uncertainty due to incomplete understanding and simplified descriptions of processes as compared to nature; (4) *Parameter uncertainty*, i.e. the uncertainties related to parameter values; (5) *Model technical uncertainty* is the uncertainty arising from computer implementation of the model, e.g. due to numerical approximations and bugs in the software and (6) *Model output uncertainty*, i.e. the total uncertainty on the model simulations taken all the above sources into account. The fact that simulated results of hydrologic models are useful in water and land resource development and decision-making for watershed management makes performing sensitivity analysis, calibration, validation and uncertainty analysis very vital while using these models.

Performance assessment of the hydrological models SWAT2005 and HSPF can lead to better understanding of the behaviour of the parameters used and to better estimate their values in order to reduce uncertainty. In this research, first sensitivity analysis was employed only using the SWAT2005 model due to the availability of sensitivity analysis tool in the model. Secondly, performance assessment of both SWAT2005 and HSPF models were performed through calibration and validation, and thirdly due to the same reason as that of sensitivity analysis, uncertainty analysis was carried out only on the model outputs from SWAT2005 using an integrated tool in the model and an independent program.

5.2 Methodology

5.2.1 General

Sensitivity analysis, optimization (calibration and validation) and uncertainty analysis of hydrological models are essential components of performance assessments to utilize the models for planning and decision support. In this and following sections, methods used to identify most sensitive parameters, the extent to which the model predicted values approach a corresponding set of measured observations, the degree to which model-predicted values approach a linear function of measured observations, and the estimated amount by which the predicted values may depart from the true values are discussed. The general procedure of the sensitivity analysis, optimization (calibration and validation) and uncertainty analysis is provided in Figure 5.1.

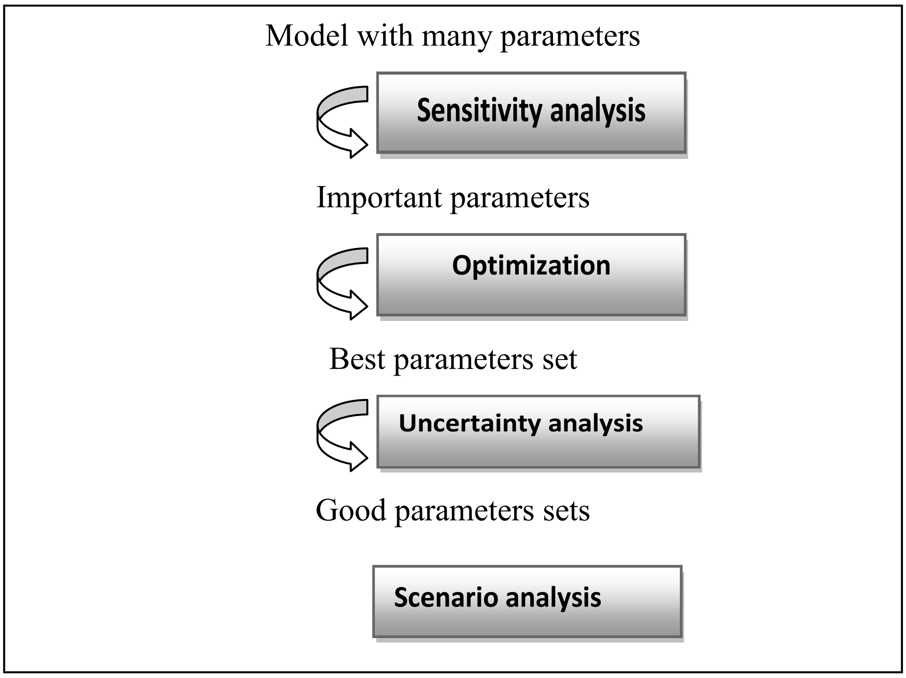


Figure 5.1 Procedures of sensitivity analysis, optimization (calibration and validation) and uncertainty analysis (after Van Griensven et al., 2006a)

5.2.2 Sensitivity Analysis

The parameter sensitivity analysis was conducted using a combined method of Latin Hypercube (LH) sampling and One-Factor-At-a-Time (OAT), a LH-OAT that is integrated to SWAT2005. ***LH sampling procedure*** is a sophisticated way to perform random sampling that allows a robust analysis requiring not too many runs (McKay et al., 1979). The concept of the LH is based on the Monte Carlo simulation but uses a stratified sampling approach that allows efficient estimation of the output statistics. First, the distribution of each parameter is subdivided into m ranges, each with a probability of occurrence equal to $1/m$. Next, random values of the parameters are generated ensuring that each range is sampled only once. Then, the model is run m times with the random combinations of the parameters (van Griensven et al., 2006a; Arabi et al., 2006).

On the other hand ***OAT*** design is an example of an integration of a local to a global sensitivity method. It is a technique that falls under the category of screening methods (Saltelli et al., 2000). In the OAT, each model run involves perturbation of only one parameter in turn. This way, the variation of model output can be unambiguously attributed to the perturbation of the corresponding factor. The output analysis is based on the study of the random sample of observed elementary effects, which are generated from each considered input.

A ***LH-OAT*** therefore combines the OAT design and LH sampling by taking the LH samples as initial points for an OAT design. As a result, the LH-OAT sensitivity analysis is a robust and efficient method: for m intervals in the LH-method, a total of $m \cdot (p+1)$ runs are required. The LH-OAT provides ranking of parameter sensitivity based on the final effects. Thus, using this technique the sensitivity of model output to a given parameter is assessed across the entire feasible range for that parameter and across a number of different values for other parameters in the model, thus incorporating a limited amount of parameter interaction.

Accordingly, sensitivity analysis was performed for 27 parameters that may have a potential to influence Hare river flow (Table 5.1). The ranges of variation of these parameters are based on a listing provided in the SWAT2005 manual (Neitsch et al., 2005) and are sampled by considering a uniform distribution.

Table 5.1 Parameters and parameter ranges used in sensitivity analysis using SWAT model

Name	Description	Max	Min	Process
CN2	SCS runoff CN for moisture condition II	35	98	Runoff
SURLAG	Surface runoff lag coefficient	0	10	Runoff
SOL_AWC	Available water capacity of the soil layer (mm/mm soil)	0	1	Soil
SOL_K	Soil conductivity (mm/hrs)	0	100	Soil
SOL_Z	Soil depth	0	3000	Soil
EPCO	Plant evaporation compensation factor	0	1	Evaporation
ESCO	Soil evaporation compensation factor	0	1	Evaporation
SOL_ALB	Soil albedo	0	0.1	Evaporation
ALPHA_BF	Baseflow alpha factor (days)	0	1	Groundwater
GW_DELAY	Groundwater delay (days)	0	50	Groundwater
GW_REVAP	Groundwater 'revap' coefficient.	0.02	0.2	Groundwater
GWQMN	Threshold depth of water in the shallow aquifer required for return flow to occur (mm)	0	5000	Groundwater
RCHR_DP	Groundwater recharge to deep aquifer (fraction)	0	1	Groundwater
REVAPMN	Threshold depth of water in the shallow aquifer for 'revap' to occur (mm).	0	500	Groundwater
SLOPE	Average slope steepness (m/m)	0.0001	0.6	Geomorphology
SLSUBBSN	Average slope length (m).	10	150	Geomorphology
CH_N1	Manning coefficient for tributary channel	0.008	30	Channel
CH_K1	hydraulic conductivity in tributary channel (mm/hrs)	0	150	Channel
CH_ S1	Average slope of tributary channel (m/m)	0	10	Channel
CH_N2	Manning coefficient for main channel	0.008	0.3	Channel
CH_ S2	Average slope of main channel (m/m)	0	10	Channel
CH_K2	hydraulic conductivity in main channel (mm/hrs)	0.01	150	Channel

One parameter was adjusted while others were kept unchanged. For each parameter, changes were made a number of times within its allowable range to test its sensitivity. Results are discussed in section 5.3.

5.2.3 Calibration and Validation

In this study, the performances of the SWAT2005 and HSPF models were conducted through calibration and validation procedures. Model calibration involves adjustment of parameter values of models to reproduce the observed response of the Hare watershed within the range of accuracy specified in the performance criteria. Consequently, tests were conducted to validate the calibrated model that is capable of making sufficiently accurate predictions. This requires using the calibrated model, without changing the parameter values, to simulate the response for a period other than the calibration period. The model is said to be validated if its accuracy and predictive capability in the validation period have been proven to lie within acceptable limits.

The approach to calibrate and validated the SWAT2005 model was based on manual calibration helper and auto-calibration procedures. Both of these options have been integrated in the new versions of SWAT2005. The automatic approach is based on the Shuffled Complex Evolution algorithm, developed at the University of Arizona (SCE-UA) (Duan et al., 1992), which is a global search algorithm for the minimization of a single function. SWAT2005 auto-calibration tool uses the Parameter Solution (ParaSol) (van Griensven and Meixner, 2006) method that aggregates objective functions (OF) into a Global Optimization Criterion (GOC) and then minimizes these OF's or a GOC using the SCE-UA algorithm. The uncertainty analysis could then be performed with a choice between two statistical concepts.

One of the objective functions used in ParaSol is Sum of the squares of the residuals (SSQ) that aims at matching a simulated series to a measured time series:

$$SSQ = \sum_{i=0}^{n} \left(q_{obs} - q_{sim}\right)^2 \quad (5.1)$$

Actually, the SCE-UA combines the direct search method of the simplex procedure with the concept of a controlled random search, a systematic evolution of points in the direction of global improvement, competitive evolution and the concept of complex shuffling. In a first step (zero-loop), SCE-UA selects an initial "population" by random sampling throughout the feasible parameters space for P parameters to be optimized (delineated by given parameter ranges). The population is divided into several "complexes" that consist of 2p+1 points. Each complex evolves independently using the simplex algorithm. The complexes are periodically shuffled to form new complexes in order to share information between the complexes.

SCE-UA has been widely used in watershed model calibration and other areas of hydrology such as soil erosion, subsurface hydrology, remote sensing and land surface modeling (Duan et al., 2003). It was generally found to be robust, effective and efficient. The SCE-UA has the advantages that the computer does the hard work of exploring the parameter space, rather than the user, and requires that performance is specified by an objective function. Moreover, the development of automatic methods has allowed detailed investigation of the issues underling the search for a global optimum set of parameter values in a way that was not possible using a manual approach. During the calibration process Parameters that govern surface water processes, subsurface water processes, and parameters that influence routing processes were considered based on the sensitivity analysis result.

During the calibration of the HSPF model, first manual calibration suggest in the Expert System of HSPF (HSPEXP) for water balance, low flow, storm flow, and seasonal adjustments was followed. Normally, during each of the four major phases, a different set of calibration parameters is evaluated by comparing simulated streamflow with observed streamflow. Thus, the hydrology calibration of HSPF using HSPEXP was done in four steps: (1) An overall water mass balance was developed by adjusting precipitation, evapotranspiration, and loss to deep groundwater; (2) Adjusting the high-flow/low-flow distribution by adjusting percolation rates, groundwater recharges, and re-emergence of water to streams; (3) Matching peak storm volumes and adjusting the number of days required for flow to return to normal levels and (4) Fitting the seasonal distribution of flows considering the seasonal variation in evapotranspiration, soil moisture, and changes in groundwater recharge to streams

For running HSPEXP, eight output time series, simulated total runoff (SIMQ), simulated surface runoff (SURO), simulated interflow (IFWO), simulated baseflow (AGWO), potential evapotranspiration (ET) (PETX), simulated actual ET (SAET), upper zone storage (UZSX), and lower zone storage (LZSX) were required. The default HSPEXP criteria (Table 5.2) for evaluating the accuracy of the flow simulation were used in the calibration process.

Table 5.2 Default criteria for HSPEXP

Variable	***Percent Error***
Total volume	10%
50% Lowest Flows	10%
10% Highest Flows	15%
Storm Peaks	15%
Seasonal Volume Error	10%

Finally, the performance of the models was checked using coefficient determination (R^2, Eqn. 5.2) and the Nash-Sutcliffe model efficiency (E_{NS}, Eqn. 5.3) (Nash and Sutcliffe, 1970). Model calibration was considered satisfactory if the simulated quantity was within 20% of observed data, R^2 was greater than 0.6, and E_{NS} was greater than 0.5. Parameter optimization is thus based on these evaluation criteria on both daily and monthly basis.

$$R^2 = \left\{ \frac{\sum_{i=1}^{n}(q_{obs} - \overline{q_{obs}})(q_{sim} - \overline{q_{sim}})}{[\sum_{i=1}^{n}(q_{obs} - \overline{q_{obs}})^2]^{0.5}\,[\sum_{i=1}^{n}(q_{sim} - \overline{q_{sim}})^2]^{0.5}} \right\} \quad (5.2)$$

$$E_{NS} = 1 - \frac{\sum_{i=1}^{n}(q_{sim} - q_{obs})^2}{\sum_{i=1}^{n}(q_{obs} - \overline{q_{obs}})^2} \quad (5.3)$$

As can be seen from equations 5.1 and 5.3, the relationship between E_{NS} and *SSQ* is:

$$E_{NS} = 1 - \left(\frac{SSQ}{\sum_{i=1}^{n}(q_{obs} - \bar{q}_{obs})^2} \right)$$

(5.4)

Where q_{obs} is the observed daily discharge in (m^3s^{-1}), q_{sim} is the simulated daily discharge (m^3s^{-1}), $\bar{q}_{obs}$ is the mean observed daily discharge (m^3s^{-1}) and $\bar{q}_{sim}$ is simulated mean value.

The coefficient of determination is an indicator of strength of relationship between the observed and simulated values. On the other hand, Nash-Sutcliffe coefficient indicates how much the model accurately simulated the natural process with E_{NS}=1 most accurate and has a range of values from $-\infty$ to 1. Moreover, equation 5.4 indicates a one-to one relationship and thus, all the objective function values in using the ParaSol approach are converted to E_{NS} for the convenience of comparison. This method however, mainly accounts for the parameter uncertainty, problems associated with badly defined objective function and model structure/hypothesis will lead to biased results, and hence underestimate the prediction uncertainty.

A discharge data for the period 1980-2004 was utilized to calibrate and validate both models. However, due to the gap between the land use and land cover map (1975) and streamflow initial period 1980, adjustments were made on the CN to account for the land use and land cover change from 1975 to 1981 before running simulation for calibration of the model. The adjustments were made based on the rate of LUCC during the period 1975-2004. The set of data was then divided in to two sets (1981-1990 and 1992-2004) based on the newly adjusted 1981 and 2004 land use and land cover data. Both periods were again divided in to two for calibration and validation. The first halves (1981-1984 and 1992-1995) were used for to calibrate the model while the second halves (1985-1990 and 1996-2004) were used to assess the validity of the calibration for the two periods. Results are discussed in section 5.3.

5.2.4 Uncertainty Analysis

5.2.4.1 The ParaSol and SUNGLASSES Methods

In any (hydrological) modeling work there are uncertainties in input (e.g., rainfall), in conceptual model (e.g., by process simplification or by ignoring important processes), in model parameters (non-uniqueness) and in the measured data (e.g., discharge used for calibration). As mentioned in section 5.1, uncertainty analysis was performed only on SWAT2005 model outputs. The uncertainty analysis tool of SWAT2005 has two options, namely Parameter SOLution (ParaSol) with Uncertainty Analysis method and Sources of UNcertainty GLobal Assessment using Split SamplES (SUNGLASSES).

As described in the previous sub-section, ParaSol is an optimization and statistical method for the assessment of parameter uncertainty that can be classified as being global, efficient and being able to deal with multiple objectives. On top of ParaSol, SUNGLASSES uses a split sample approach to estimate overall model predictive uncertainty, and these results are compared to those gathered using a previously developed parametric uncertainty method based on statistical approaches, ParaSol. SUNGLASSES aim at detecting additional sources of uncertainty by using an evaluation period in addition to the calibration period. It was designed to assess predictive uncertainty that is not captured by the parameter uncertainty estimated by ParaSol. This method accounts for strong increases in errors when simulations are done outside the calibration period by using a split sample strategy whereby the validation period is used to set uncertainty ranges (van Griensven & Meixner, 2003).

Uncertainty analysis with ParaSol operates by a parameter search method for model parameter optimization of a modified version of the SCE-UA method followed by a statistical method that uses the model runs that were performed during the optimization to provide parameter uncertainty bounds and the corresponding uncertainty bounds on the model outputs. The simulations gathered by SCE-UA are very valuable as the algorithm samples over the entire parameter space with a focus of solutions near the optimum/optima. After the optimization of the modified SCE-UA, the simulations performed are divided into ‘good’ simulations and ‘not good’ simulations to get ‘good’ parameter sets and ‘not good’ parameter set. A threshold value is defined either by the Chi-Square ($\chi 2$) statistics where the selected simulations correspond to the Confidence Region or Bayesian statistics that are able to point out the HPD for the parameters or the model outputs (van Griensven and Meixner, 2003). The prediction uncertainty is hence constructed equally from the ‘good’ simulations. In this research both the ParaSol and SUNGLASSES options of SWAT2005 were employed.

5.2.4.2 The Sequential Uncertainty Fitting (SUFI-2) Method

The Sequential Uncertainty Fitting, ver. 2 (SUFI-2) is one of the uncertainty analysis programs that is incorporated in an independent program called SWAT Calibration and Uncertainty Program (SWAT-CUP) (Abbaspour, 2007) that perform uncertainty analysis due to both Parameter and model uncertainties. SUFI-2 is developed for a combined calibration and uncertainty analysis. It is a multi-site, semi-automated global search procedure and the objective function was formulated as the E_{NS} coefficient between the measured and simulated discharges. The program maps the aggregated uncertainties to the parameters and aims to obtain the smallest parameter uncertainty ranges. In SUFI-2, parameter uncertainty is depicted as uniform distributions. The parameter uncertainty leads to uncertainty in the output which is quantified by the 95% prediction uncertainty (95PPU) calculated at the 2.5% (L95PPU) and the 97.5% (U95PPU) levels of the cumulative distribution obtained through Latin hypercube sampling (Schuol and Abbaspour 2006).

Starting from initially large but meaningful parameter ranges that bracket ‘most’ of the measured data within the 95PPU, SUFI-2 is iterated until an optimum solution is reached.

After each iteration, new and narrower parameter uncertainties are calculated where the more sensitive parameters find a larger uncertainty reduction than the less sensitive parameters. In deterministic simulations, output (i.e., river discharge) is a signal and can be compared to a measured signal using indices such as coefficient of determination (R^2), root mean square error, or Nash-Sutcliffe. In stochastic simulations where predicted output is given by a prediction uncertainty band instead of a signal, two different indices were devised to compare measurement to simulation: the *P-factor* and the *R-factor* (Abbaspour et al., 2007).

Two stopping rules quantifying the uncertainty are defined: (1) bracketing "most" of the measured data within the 95PPU band *(P-factor)*, and (2) obtaining a "small" ratio of the average distance between the 2.5^{th} and 97.5^{th} prediction percentiles and the standard deviation of the measured data (*R-factor*). These two measures quantify the model uncertainty. The ideal situation would be to account for 100% of the observed data in the 95PPU while at the same time have an *R-factor* close to zero. But this is seldom the case because of measurement errors, conceptual model uncertainty, and non-uniqueness issues. The values of the percentage of bracketed data, *R-factor*, as well as the R^2 and E_{NS} between the observation and the best simulation determine the strength of a calibrated mode.

5.2.4.3 The Generalized Likelihood Uncertainty analysis Extension (GLUE) Method

The Generalized Likelihood Uncertainty analysis Extension (GLUE) is also one of the programs incorporated in SWAT-CUP (an independent program) that and partly allows for the possible non-uniqueness (equifinality, ambiguity or non-identifiability) of parameter sets during the estimation of model parameters in over-parameterized models. Its development arose out of dissatisfaction with an optimization approach to model calibration and with the assumptions of statistical models of "measurement error" in representing model uncertainties (Beven and Binley, 1992). The starting point for the GLUE concepts is the rejection of the idea of an optimum parameter set in favour of the concept of *equifinality* of model structures and parameter sets. A priori any model structure and parameter set that predicts a required variable in an application is a *potentially* useful simulator. However, it is often very difficult to accept that a particular model structure or parameter set (or even area of the parameter space) is dominant in fitting available observations. It is only possible to evaluate the relative performance of the range of possible models, either qualitatively or quantitatively in terms of some likelihood measure.

The procedure is simple and requires few assumptions when used in practical applications. The technique is based on the estimation of the weights or probabilities associated with different parameter sets, based on the use of a subjective likelihood measure to derive a posterior probability function, which is subsequently used to derive the predictive probability of the output variables. This method is usually applied by directly likelihood weighting the outputs of multiple model realizations to form a predictive distribution of a variable of interest. Parameter sets with likelihood measures above and below that threshold are then considered to be 'behavioural' and 'non-behavioural' respectively. Prediction uncertainties are then related to variation in model outputs, without necessarily adding an additional explicit error component.

Recently Beven (2005) states that "these prediction limits will be conditional on the choice of limits of acceptability; the choice of weighting function; the range of models considered; any prior weights used in sampling parameter sets; the treatment of input data error, etc. However, given the potential for input and model structural errors, they (the choices) will not guarantee that a specified proportion of observations, either in calibration or future predictions, will lie within the tolerance or prediction limits (the aim, at least, of a statistical approach to uncertainty) nor is this necessarily an aim in the proposed framework". Thus, the GLUE methodology focuses attention on the subjective elements of model evaluation, choice of likelihood measure and choice of threshold value, but requires that those elements be defined explicitly and therefore made open to debate and justification.

The GLUE approach has been used for uncertainty analysis in different models and fields. For instance, Freer and Beven (1996) evaluated uncertainty of TOPMODEL parameters by applying GLUE approach. They presented sensitivity of the results on various performance measures and assessed application of Bayesian theory to update 4-year continuous simulation of daily runoff at the end of each year. Christiaens and Feyen (2002) applied GLUE for calibration and uncertainty analysis of soil hydraulic parameters in MIKE SHE model. Moreover, the GLUE approach has been applied to other fields of hydrology and hydraulics, e.g., soil erosion prediction (Brazier et al. 2001), capture zone delineation (Feyen et al. 2001), and flood inundation prediction (Hunter, et al.2005).

However, in two recent evaluations of GLUE, Christensen (2003) and Montanari (2005) both found that GLUE tends to underestimate the true prediction uncertainty associated with modeled streamflow. Results in these researches demonstrate that prediction limits derived from GLUE can be significantly different from prediction limits derived from correct classical and widely accepted statistical methods. However, more arguments in favour of the GLUE approach have been rehearsed elsewhere (Beven and Young, 2003; Arabi et al., 2006; Schuol and Abbaspour 2006).

5.3 Results and Discussions

5.3.1 Sensitivity Analysis

The SWAT2005 model outputs depend on many input parameters related to the soil, land use, management, weather, channels and aquifer. Therefore, modeling LUCC impact with SWAT2005 necessitates evaluation of the sensitivity of flow output to the selected parameters. The sensitivities to the model performance give insight in parameter identifiability using the available information daily streamflow data. In this research, a LH-OAT sensitivity analysis, which is incorporated in SWAT2005, is used to perform sensitivity analysis. The analysis was carried out based on the objective function of the SSQ for all the 24 models parameters and 10 intervals of LH sampling. After set-up the SWAT2005 model and incorporating all the input parameters simulations were carried out and sensitivity analysis was run for the period 1992-2004.

The result of the analysis indicates that eight parameters namely; Curve number (CN), Soil Available Water Capacity (SOL_AWC), Soil depth (SOL_Z), Soil Evaporation Compensation factor (ESCO), Saturated hydraulic conductivity (SOL_K), Slope (SLOPE), Groundwater “revap” coefficient (GW_REVAP) and Groundwater recession factor (ALPHA_BF) are the most crucial parameters for the studied watershed (Table 5.3).

Table 5.3 Sensitivity ranking, and category of the most sensitive parameters

Parameters	**Sensitivity rank**	***Category***	**Description**
CN2	1	Very High	SCS runoff curve number for moisture condition II
SOL_AWC	2	Very High	Available water capacity of the soil layer (mm/mm soil)
SOL_Z	3	High	Soil depth (mm)
ESCO	4	High	Soil evaporation compensation factor
SOL_K	5	High	Saturated Hydraulic conductivity (mm/hr)
SLOPE	6	High	Average slope steepness (m/m)
GW_REVAP	7	High	Groundwater ‘revap’ coefficient.
ALPHA_BF	8	High	Baseflow alpha factor (days)

The sensitivity analysis indicated the overall importance of the eight parameters in determining the streamflow at the study area. However, CN2 and SOL_AWC were found to be very crucial than other parameters. All the eight parameters generally govern the surface and subsurface hydrological processes and stream routing. It is important to note that each of these parameters was treated in an identical manner across different sub-watersheds or HRU’s during the calibration and validation processes. This result illustrates how parameter sensitivity is site specific and depends on land use, topography and soil types, as compared to other studies elsewhere.

5.3.2 Calibration and Validation

The SWAT2005 Model

The SWAT2005 model is first calibrated against the measured streamflow data for the periods of 1981-84 and 1992-95 as discussed in the previous section. The simulated hydrographs were compared to the observed hydrographs at gauging site. The first one year of the simulation were used as a model “warm-up” in order to establish proper initial conditions and stabilize the model. Goodness-of-fit measures were evaluated to test the model’s accuracy. Model calibration was carried out on daily and monthly bases through fine adjustments on the basic parameters already identified. An initial annual calibration was followed by monthly and daily calibrations. Streamflow was calibrated until monthly and daily $R^2 > 0.6$ and $E_{NS} > 0.5$ (Santhi et al., 2001).

Three additional parameters (SLOPE, SLSUBBASIN, and GW_REV) other than those identified during sensitivity analysis were used during calibration primarily due to the goal of matching the model as closely as possible to processes naturally occurring in the watershed. These parameters were identified based on the results of groundwater analysis, future scenarios to be analyzed and calibration parameters identified in other published results. Subsequently, the measured and predicted streamflow was validated on the same time steps for the periods of 1988-90 and 2000-03. The results of the model calibration and validation are given in Table 5.4 and Figure 5.2.

Table 5.4 SWAT2005 performance during the calibration and validation periods

Index	**1975 LUC map**				**2004 LUC map**			
	Calibration (1981-84)		Validation (1988-90)		Calibration (1992-95)		Validation (2000-03)	
	Daily	Mon.	Daily	Mon.	Daily	Mon.	Daily	Mon.
Coeff. det. (R^2)	0.76	0.73	0.82	0.72	0.79	0.85	0.77	0.80
N-S coeff. (E_{NS})	0.64	0.67	0.57	0.66	0.75	0.80	0.63	0.73

The performance efficiency values in both the calibration and validation phases prove that SWAT2005 predicted measured streamflow quite satisfactorily for monthly and daily streamflow time steps. As indicated in the Table, the monthly coefficient of determination values range from 0.72 to 0.85 and daily from 0.76 to 0.82 and likewise, the E_{NS} varies from 0.57 to 0.75 for daily and 0.66 to 0.80 for monthly calibrations and validations with the highest R^2 and E_{NS} values being during the calibration of the model for the 2004 land use and land cover condition.

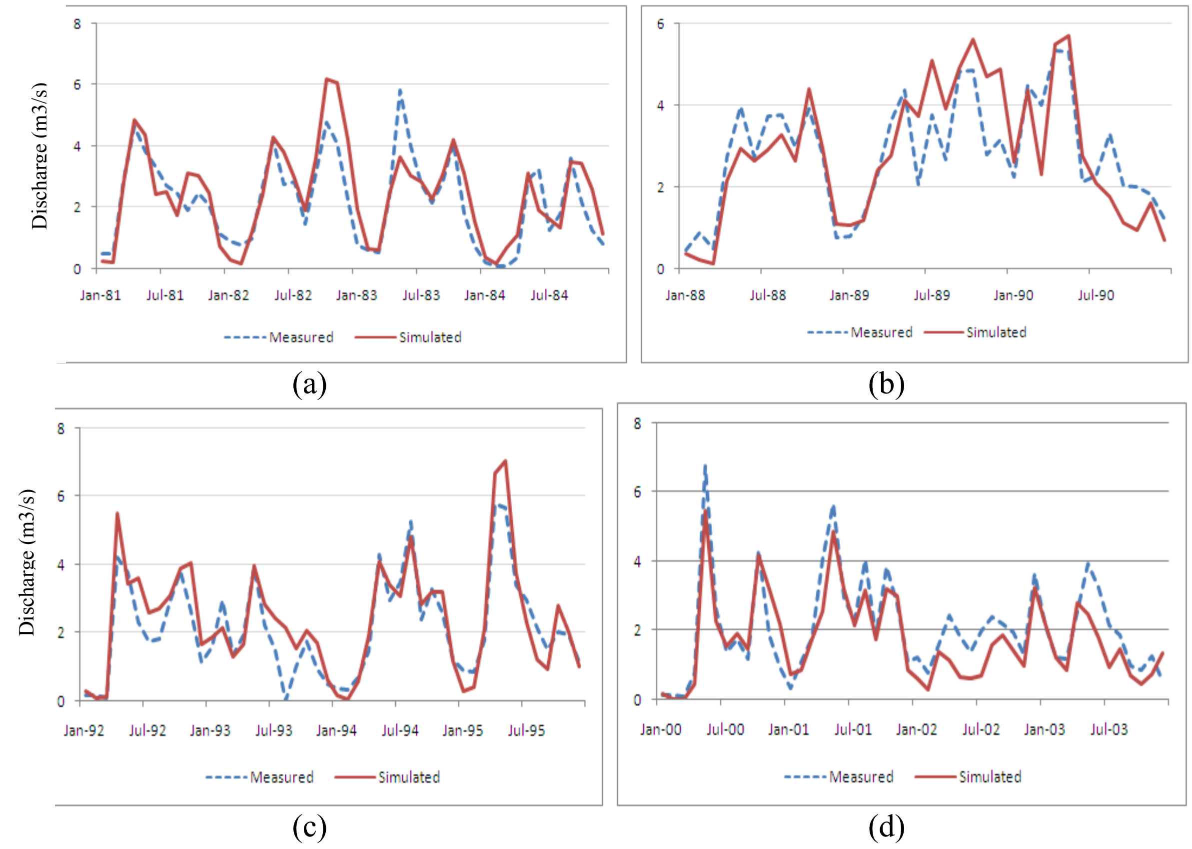


Figure 5.2 Monthly calibration (a & c) and validation (b & d) for the study periods

Figure 5.2 above clearly presents the graphical analysis of measured and simulated data that allows for identification of general trends in the data and differences between model simulations. This graphical interpretation together with the numerical analysis given in Table 5.4 gives a comprehensive measure of the agreement between measured and simulated data.

The HSPF Model

Like SWAT2005, simulations were made to calibrate and validate HSPF mainly for the first study period (1981-1992). This simulation is based on the meteorological and hydrological input time series belonging to the period mentioned and on the parameters found by calibration. Initially, BASINS software was used to develop the initial User Control Input (UCI) files for the basins in this study. From a BASINS project, the WinHSPF computer program was used to build a WinHSPF project and an initial HSPF simulation. An initial HSPF simulation includes, as a minimum, a WDM and UCI files. Nominal values for some parameters important to HSPF hydrology calibration are extracted from the "starter.uci" (in BASINS) and deposited into the new UCI file.

Then, the expert system HSPEXP was used to assist with calibrating and validating HSPF model. To get an overall water balance parameters such as lower zone storage nominal (LZSN), upper zone storage nominal (UZSN) and deep groundwater (DEEPFR) were adjusted. Then, various calibration parameters were adjusted to test how well the simulated flow matches observed streamflow at the outlet of Hare watershed. These parameters include soil infiltration rate (INFILT), fraction of potential ET that can be satisfied from baseflow (BASETP), fraction of potential ET that can be satisfied from active groundwater storage (AGWETP), groundwater recession rate (AGWRC), coefficient measuring transition from surface water detention storage to interflow (INTFW) and the interflow recession coefficient. The final calibrated hydrological parameters are given in Table 5.5.

Table 5.5 HSPF model parameter adjusted during calibration

Parameter	***Definition***	***Initial value***	***Recommended range***
LZSN	Lower zone nominal storage, mm	220	60.5-380
INFILT	Index to infiltration capacity, mm/h	1.8-16.5	0.2-17.5
UZSN	Upper zone nominal storage, mm	18.5	0.5-55.5
BASETP	Fraction of PET from baseflow	0-0.15	0-0.3
AGWETP	Fraction of PET from active groundwater storage	0-0.001	0-0.3
LZETP	Lower zone ET parameter	0.1-0.8	0.1-0.9
INTFW	Interflow inflow parameter	1.0-2.1	1.0-9.5
IRC	Interflow recession parameter, per day	0.6	0.001-0.99
AGWRC	Groundwater recession parameter, per day	0.99	0.001-0.99
DEEPFR	Fraction of groundwater inflow to inactive groundwater	0.0	0-0.2

Figure 5.3 shows observed and simulated flow plotted against time at the outlet of Hare watershed corresponding to calibration and validation periods. The relative errors between simulated and observed flows were 7.4% for the calibration period and 8.6% for the validation period; both which are within the required range of ± 10%. The correlation coefficients and the Nash-Sutcliffe coefficient of HSPF model for calibration and validation periods are given in Table 5.6 and were above the criteria set.

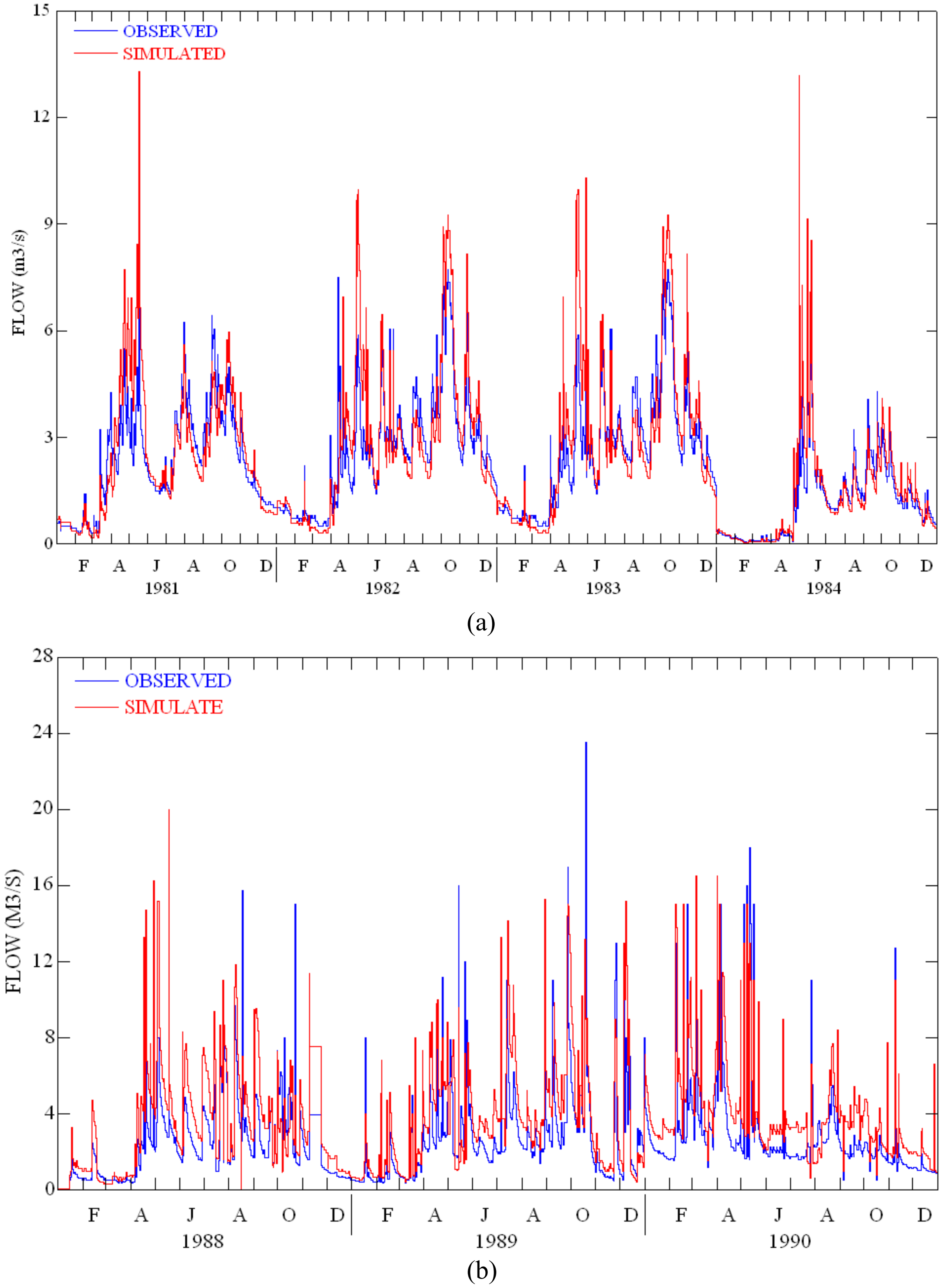


Figure 5.3 Daily calibration (a) and validation (b) results using the HSPF model

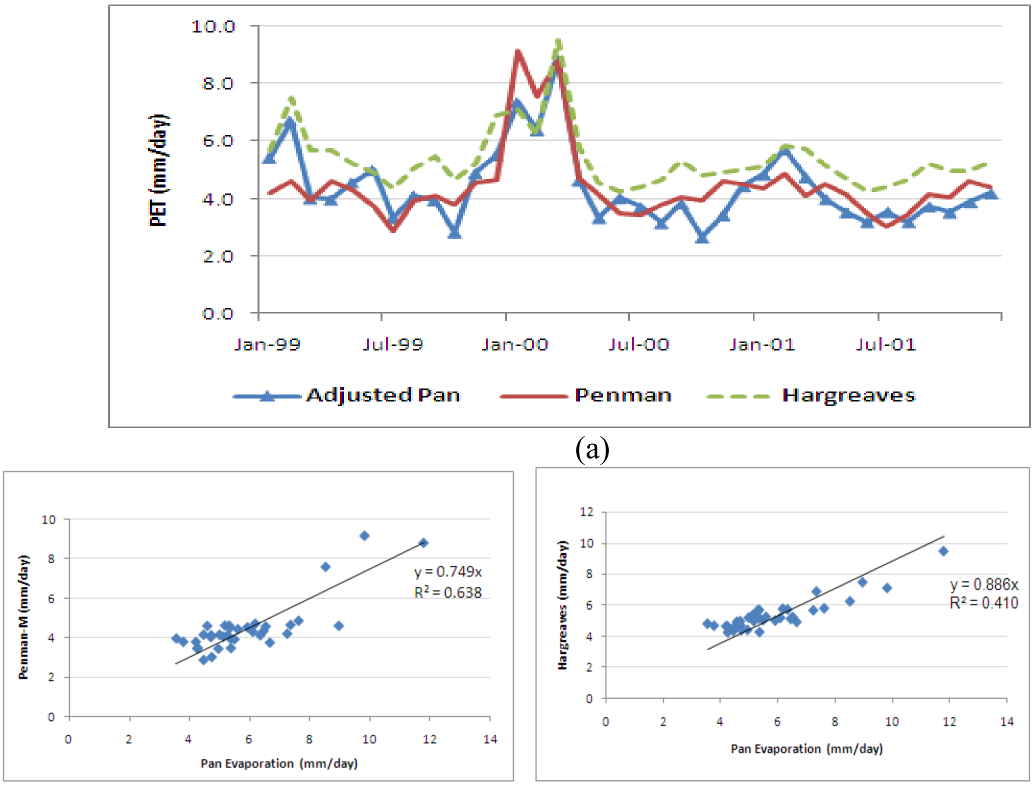
Table 5.6 HSPF performance during the calibration and validation periods

Index	Calibration (1981-84)		Validation (1988-90)	
	Daily	Mon.	Daily	Mon.
Coefficient of deter. (R^2)	0.70	0.71	0.67	0.69
Nash-Sutcliffe coeff. (E_{NS})	0.62	0.63	0.58	0.64

The HSPF model was able to best reproduce both daily and monthly runoff volumes during the calibration and validation periods. However, it overestimated the peak flows during the initial phase of the calibration and even after calibration of the model.

On the other hand, an attempt was made to compare evapotranspiration (ET) obtained from SWAT2005 with modified Penman and Hargreaves methods, and a measured pan evaporation data at Arba Minch station. Our ability to estimate actual regional evapotranspiration is often constrained by models that treat potential evapotranspiration as an independent climatic forcing process, often an empirical function of pan evaporation observed at nearby weather stations, or by models that tend to rely on gross assumptions as to the nature of moisture dynamics in each of the components of the land surface–atmosphere interface and of the interactions between them (Hobbins et al., 2001).

A “Class A” evaporation pan data for the period 1999-2001 was used for this purpose. For the “Class A” evaporation pan, the coefficient of pan varies between 0.35 and 0.85 and usually a value of 0.70 (FAO, 1986) or 0.75 (Willson, 1990) is adopted. In a previous study on the Abaya-Chamo Basin, Seleshi (2001) has used coefficient value 0.85 for pan evaporations. However, for this research the coefficient of pan was computed using the available data and a coefficient of 0.8 was adopted. Figure 6.10 presents the graphical representation of the comparisons of the adjusted Pan Evaporation data and SWAT2005 PET with modified Penman and Hargreaves methods.



(a)

(b) (c)

Figure 5.4 PET using adjusted pan, Penman and Hargreaves methods (a) and correlation coefficients between Penman and adjusted pan (b) and Hargreaves and adjusted pan (c).

As indicted in Figure 4.10, the Hargreaves method overestimated PET and will result in a higher ET and, therefore, the simulated monthly discharge will be lower than the observed values if this method is employed. The correlation coefficient result indicates that there is significant relation (0.64) between the modified Penman Method and the adjusted pan evaporation value. On the other hand, the correlation between the adjusted pan evaporation data and the Hargreaves method is lower (0.41) that could be due to the over estimation of evaporation using this method.

5.3.3 Uncertainty Analysis

The computational procedures described in sub-section 5.2.2 were performed to quantify the uncertainty associated with model simulations. Uncertainty analysis was implemented after sensitivity analysis, calibration and validation processes, using the ParaSol and SUNGLASSES methods of SWAT2005, and the GLUE and SUFI-2 methods of SWAT-CUP.

All the identified parameters were employed for the automatic uncertainty analysis with ParaSol and SUNGLASSES methods. The results of the uncertainty analysis using these methods are provided in Table 5.7 below.

Table 5.7 Explicit calibrated parameters

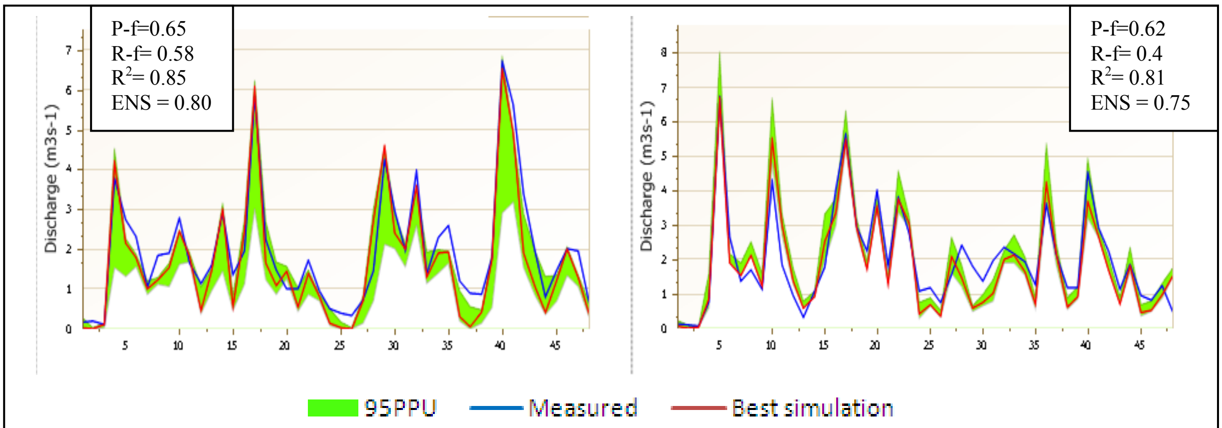
Parameter	*SWAT2005 default*		*Actually used*	*Uncertainty ranges*				*Type of change*
				ParaSol		**SUNGLASSES**		
	Lower bound	**Upper bound**		**Min**	**Max**	**Min**	**Max**	
CN2	35	98	60 to 81	-5.2	10.5	-7.9	12.3	Relative*
SOL_AWC	0	1	0.07 to 0.14	-3.1	24.0	-4.1	28.0	Relative
SOL_Z	0	3000	150-450	-0.10	0.10	-0.10	0.10	Relative
ESCO	0	1	0.85	0.45	0.91	0.28	1.00	Value
SOL_K	0	100	3.5 to 72	-0.15	0.35	-0.18	0.40	Relative
SLOPE	0.0001	0.6	0.07 to 0.6	-21.9	20.8	-21.9	24.1	Relative
ALPHA_BF	0	1	0.26	0.46	0.69	0.38	1.00	Value
GW_DELAY	0	50	20	1.18	9.01	-2.73	9.44	Relative
EPCO	0	1	0.95	0.39	0.64	0.20	0.87	Value
SLSUBBSN	10	150	10 to 45.7	-0.22	0.05	-0.25	0.10	Relative

*Relative change in percentage

The uncertainty using the ParaSol and SUNGLASSES reveal optimized values for each of the parameters considered. The uncertainty associated with parameters that are determined based the different watershed attributes are assumed to be reduced due to the use of better spatial resolution for these attributes. Conversely, uncertainties of parameters that are not determined from those attributes are reduced with calibration procedure through a systematic range adjustment process.

As indicated in the Table, the result that SUNGLASSES has a much larger uncertainty bound than the ParaSol method that indicates other causes of uncertainty are involved including: the inaccuracy in the data set to identify the important processes, model structural errors, and model discretization errors. The latter sources are likely true of most distributed environmental models as they share many of the attributes of distributed models (processes scaled up from point scale to landscape scale, multiple criteria to meet, and inadequate data availability to properly parameterize these models). SUNGLASSES operate not only as a validation procedure for the model structure but also as a validation of the ParaSol uncertainty procedure of the model. This is reflected by the maximum and minimum values presented in Table 6.8. Moreover, the uncertainty bounds associated with absolute predictions of the SWAT2005 model were larger than the ones corresponding to the value of data collected from the field.

The result of the uncertainty analysis from SUFI-2 of the SWAT-CUP program is presented in Figure 5.5. The program provides an overview of the model performance using the *P-factor* (percent data bracketed) and the *R-factor* (a measure of the thickness of the 95PPU band) for the calibration and validation periods of 1992-2004. In addition, the efficiency criteria calculated based on the observed and the "best" simulation (i.e., simulation with the largest value of the objective function), and the E_{NS} coefficient is also provided.



(a) (b)

Figure 5.5 Monthly calibration (a) and validation (b) results showing the 95% prediction uncertainty intervals along with the measured discharge

The above Figure illustrates the 95PPU intervals of the last iteration for an extract of the calibration and validation for the periods of 1992-1995 and 2000-2003 respectively. In the calibration iteration, 65% (p=0.65) of the observed monthly streamflow was bracketed by the 95PPU, and *R-factor* of 0.58 was attained that indicates SUFI-2 was able to capture most uncertainties. Moreover, the coefficient of correlation and Nash-Sutcliffe coefficients were 0.85 and 0.80 respectively that are comparable the one determined using the ParaSol method. In subsequent iterations for the validation period 62% (p=0.62) of the stream flow was bracketed by the 95PPU and *R-factor* was reduced (d=0.4) but still indicates there are still some model uncertainties. However, the striking balance between p-factor and R-factor demonstrates that model and parameter uncertainties reduced to reasonable degrees. The parameter ranges that were identified using the SUFI-2 method for the period of 2000-2003 are presented in Table 6.7 together with the one determined using the GLUE method.

The result of the uncertainty analysis from GLUE is presented in Figure 5.6. After incorporating all the GLUE inputs that were obtained from the SWAT2005 simulations, the SWAT-CUP was simulated with the GLUE option for a similar period as that of SUFI-2.

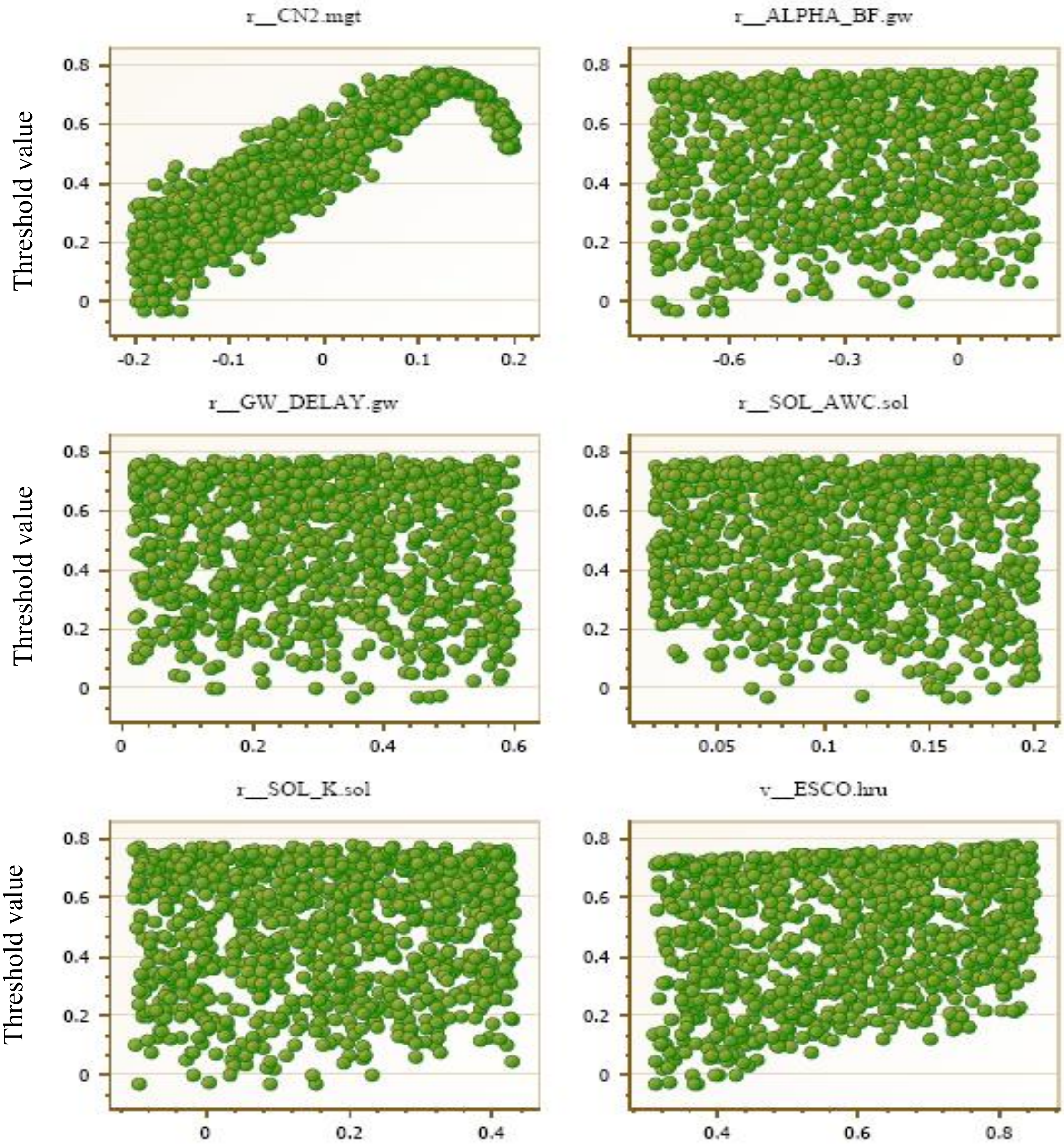


Figure 5.6 Dotty plots of the uncertainty output from GLUE

Uncertainty analyses with six parameters are presented to identify using the GLUE method. During the simulation a likelihood measure (E_{NS}) was used and a threshold level of 0.65 was used to set each parameter as "behavioral" and "non-behavioral" from a randomly sampled prior distribution. As indicated in Figure 6.12, a likelihood measure of 0.8 was attained and it is imperative to observe that the Curve number (r_CN.mgt) increases towards this value with a relative change in its value from 0 to 0.15 (an increase with 15%) and starts to drop sharply afterwards. This is a good indication that the CN used for the SWAT2005 are better determined and strength the results obtained during the sensitivity analysis, which pointed out that CN is very crucial parameter. The results from both SUFI-2 and GLUE are presented in Table 5.8.

Table 5.8 Maximum and minimum change boundaries of parameters

Parameter Name	*SUFI-2*		*GLUE*	
	Min.	Max.	Min.	Max.
r__CN2.mgt	-0.05	0.24	0.0	0.15
r__SOL_AWC.sol	-0.01	0.30	0.01	0.2
r__SOL_K.sol	-0.20	0.43	-0.10	0.40
v__ALPHA_BF.gw	0.24	0.79	0.66	0.95
v__GW_DELAY.gw	29.0	40.0	25.0	40.0
v_Esco	0.36	0.89	0.40	0.90

r__ means relative change (%) and v__ means value change

As illustrated in the above table, the maximum and minimum boundaries defined through both SUFI-2 and GLUE are mostly in a similar range except for few exceptions. However, SUFI-2 gives much more information than GLUE and also relatively better E_{NS} and R^2 values. However, the GLUE results also helps to be realistic about the uncertainty associated with the modeling process to evaluate the uncertainty limits for future events for which measured data is not available.

5.4 Conclusions

The SWAT and HSPF models were employed for Hare watershed as case study in the southern Rift Valley basin of Ethiopia to validate their performances in simulating hydrologic responses. Before calibration and validation processes, sensitivity analysis was performed using the SWAT2005 model due to the availability of an integrated sensitivity analysis tool in the model. Then, the hydrology components of both SWAT and HSPF models were calibrated and validated against the observed data collected at the watershed outlet. Finally, uncertainty analysis was performed only for SWAT2005 model outputs due to the same reason as that of sensitivity analysis and availability of an independent uncertainty analysis program for outputs from SWAT2005 model.

This study has shown that the SWAT2005 model is very sensitive to the internal and external pre-processing of the soil and land use data. The sensitivity analysis has pointed out eight crucial parameters (CN2, SOL_AWC, SOL_Z, ESCO, SOL_K, SLOPE, GW_REVAP and ALPHA_BF) that control the surface and subsurface hydrological processes of the studied watershed. However, CN2 and SOL_AWC were found to be most crucial than other parameters.

On the other hand, calibration and validation of both models have shown that the predicted values have agreed well with the observed data at the outlet of the watershed. The models are capable to estimate streamflow composition and contributions from the different land use and land cover classes. Normally, no significant differences were found in simulated runoff volumes by SWAT2005 and HSPF during the calibration period. The performance efficiency values in both the calibration and validation phases prove that both models predicted measured streamflow quite satisfactorily for monthly and daily streamflow time steps. Simulation results of the Hare watershed demonstrate that the upper sub-watershed areas are dominant as compared to surface runoff from middle reach and lower part of the watershed.

Furthermore, results of uncertainty analysis from ParaSol, SUNGLASSES, SUFI-2 and GLUE were discussed. The ParaSol method doesn't consider additional sources of uncertainty that are in general not known and not quantifiable, such as model hypothesis errors, simplifications, scaling effects or the lack of the observation period to represent, in the model, the long-term variability and fluctuations of the real world. Unlike the ParaSol that provides only parameter uncertainty analysis, the SUNGLASSES, SUFI-2 and GLUE assess total uncertainty that might be used in comprehensive decision making. Uncertainty analysis from these methods lead to more selections of parameter combinations and much wider uncertainty ranges and thus enable to assess predictive uncertainty that helps decision makers understand how uncertain their models are so that they can put the proper level of trust in computational models of the environment as they move forward to make decisions. The results here indicate that concern should be given to both the uncertainty associated with model structural error and model parametric uncertainty. However, since the underlying assumptions of the parameter uncertainty method assumed to be correct and the datasets used in SWAT2005 are adequate to translate the variability of the system into a model, the result of the SUNGLASSES, SUFI-2 and GLUE uncertainty analysis doesn't lead to larger uncertainty bounds for the model outputs when compared to ParaSol.

Although the results from calibration and validation analysis of both SWAT2005 and HSPF quite acceptable, the simulated stream flow by SWAT2005 were better than that of HSPF during the calibration and validation periods. Moreover, the availability of uncertainty analysis tool for SWAT2005 provides better insights on the sources of uncertainties and helps in the subsequent discussions. Thus, SWAT2005 was selected and used for further simulations and analysis in this research.

CHAPTER 6

Hydrological Responses to Changes in Land Use and Climate

6.1 Introduction

The hydrological impacts of land use and climate changes have received a considerable amount of interest in hydrology. LUCC is an important characteristic in the runoff process that affects infiltration, erosion, and evapotranspiration. Understanding of the effects historic land use changes and climate system have had on river flow is required to understand the future effects of land use and land cover, and climate change on hydrological regimes at a watershed level. Along with these changes, considerable consequences are expected in the hydrological cycles and subsequent effects on water resources. Early field studies to determine the effects of land management and land use change on runoff date back to the nineteenth century. Since the development of distributed and semi-distributed hydrological models, modeling the hydrological response to land use and land cover change has been a topic of active research for many research groups worldwide (e.g., Muttiah and Wurbs, (2002); Fohrer et al., (2005); Gosain, et al. (2006) amongst many others).

Theoretically, Land use and land cover, soils, and topography are the three primary watershed properties governing hydrologic variability in the form of rainfall-runoff response. While topographic characteristics can be modified on a small scale (for example, by implementing, terracing, or contour tillage), variation in watershed-scale hydrologic response through time is primarily due to changes in the type and distribution of land use and land cover. Improved understanding of the relationships between land use and land cover, climate and runoff at a watershed scale can be used to compare different part of the watershed, identify those that are at risk or susceptible to change, and aid in management attempts to limit undesired impacts. Landscape composition and its spatial variation also affects the redistribution and function rules of water in watersheds by affecting the series of processes involved in runoff formation and consequently on streamflow (Bo-Jie Fu et al., 2005).

Some studies indicate that the trends and direction in hydrologic response can be correctly inferred from the corresponding trends and direction in LUCC, predicated upon the use of comparable rainfall data in conjunction with differing land cover (Hernandez et al., 2000). The rainfall-runoff process is an integrated hydrological system within a landscape, and land use development substantially alters the spatial heterogeneity of landscape elements, which in turn change the rainfall-runoff system. Land use and land cover can also affect the direct interchange of water between streams and groundwater. The spatial distribution of shallow groundwater is widely recognised to be significant for physically realistic modelling of watershed runoff production. Changing spatial distribution of shallow saturated storage may also affect the dynamics of land–atmosphere fluxes (Lamb et al., 2003).

This chapter discusses the approach used to analyze the impacts of land use and land cover changes on streamflow and then describes ways to derive and analyze scenarios that allow assessing the influences of both land use and land cover, and climate changes at the study area. Firstly, streamflow simulations were made and analysed using SWAT2005 under current conditions using the 2004 land use and land cover map and under 'what if scenario' of the 1975 land use and land cover continues till the present time. Subsequently, two climate change and three land use and land cover change scenarios were developed and there impacts on the hydrological regime were analyzed.

6.2 Land use and climate change scenarios

Scenarios, as defined by the Intergovernmental Panel on Climate Change (IPCC 2001), are "plausible and often simplified descriptions of how the future may develop based on a coherent and internally consistent set of assumptions about driving forces and key relationships." Thus scenario analysis is an approach for evaluating various rational choices and the respective trajectories that lead to alternative future events. It is gaining widespread acceptance among decision-makers as a practical tool for addressing uncertainty about the future. The process provides the ability to explore the potential impacts, risks, benefits, and management opportunities that stem from a variety of plausible future conditions.

Designing scenarios is a widespread technique in many disciplines due to its future-oriented and flexible character and is also used for hydrological studies. The scenario is to be understood as a projection rather than a prediction. Scenario studies require experts and models from widely different disciplines and involve substantial interaction among scientists and stakeholders, as well as expert judgment. The information is combined in an iterative process of scenario definition, construction, analysis, assessment, translating model outputs to forms relevant to stakeholders, linking scenario outcomes to decision-making strategies or operational monitoring, and response. Land use and land cover, and climate change scenarios analysis provides an alternative tool to assist in explorations of the future and are prerequisite for assessing the influence of potential changes of land use and land cover, and climate on the hydrological regime (Niehoff et al, 2002; Jha et al. 2004; Veldkamp and Verburg, 2004).

The need to develop future land use and land cover change scenarios stems from the important role that human activities play in environmental quality. An understanding of how land use and land cover might evolve is required in order to estimate how people will modify their environment in the future (Rounsevell et al., 2006). The same authors employed a coherent set of land use change scenarios to Europe and discussed several technical and conceptual difficulties in developing future land use change scenarios. Pikounis et al., (2003) applied SWAT2005 to investigate the hydrological effects of different land use changes scenarios. Recently, Lin et al., (2007) used logistic regression modeling in assessing land use and hydrological processes to future land-use and climate change scenarios for watershed land use planning. Several other researchers have been undertaken to better understand, assess and project changes in land use and land cover (Veldkamp and Lambin, 2001; Parker et al., 2003; Veldkamp and Verburg, 2004; Agarwal et al. 2005; Fang et al. 2005). However, in spite of progress in integrating biophysical and socio-economic drivers of land use change, projection of impacts of future land use and climate change remains difficult.

On the other hand, the development in global climate and the impact of mankind motivated attempts to estimate the impacts of anthropogenic modification of the atmospheric composition on future climate. Climate is perceived to be changing worldwide and there has been growing concern as to the direction and effects of these changes. The IPCC was established in 1988 to provide an assessment of all aspects of climate change including how human activities can cause such changes and can be impacted by them.

According to IPCC (2007), global average temperature would rise by 1.1-6.4°C by the end of the 21st century, relative to 1980-1990, with a best estimate of 1.8-4.0°C. Similarly sea level rise in a likely range of 0.2-0.51m, an increase in global average annual precipitation and change in other local climate conditions are expected to occur as a consequence of rising global temperature. Indeed, there is already evidence that anthropogenic emissions of Greenhouse Gases (GHGs) have altered the large-scale patterns of temperature over the twentieth century (Cubasch *et al*,. 2001). Furthermore, according to UNDP Human development report (2007/2008), by the end of the 21st Century, the specter of catastrophic ecological impacts could have moved from the bounds of the possible to the probable.

In climate change studies, the widely used methods for generating climate change scenarios are Global Circulation Models (GCMs) that represent the most sophisticated attempt to date to simulate climate on a global scale. Emission scenarios are a central component of any assessment of climate change and were established to incorporate different assumptions about socio-economic, technologic and demographic development, to estimate the increase in GHGs. GCMs currently offer the most credible methods of simulating global climate responses to increased GHGs concentrations, and provide estimates of climate variables (Houghton et al., 2001; Prudhomme et al. 2003; Baede *et al.* 2001; Washington et al., 2004).

There are wide ranges of GCM models identified by the IPCC (2001) for impact assessment studies. Among these, HadCM3 (Hadley Centre for Climate Prediction and Research Coupled Model, UK), ECHAM (Climate Research Centre, European Centre/Hamburg Model, Germany), CGCM (Canadian Centre for Climate Modeling and Analysis, GFDL_R30 (Geophysical Fluid Dynamics Laboratory & NOAA), and CCSR/NIES (Centre for Climate Systems Research & Japanese National Institute for Environmental Studies) are the commonly used ones. Consequently, the Special Report on Emission Scenarios (SRES) of the IPCC describes six different scenario groups drawn from a four different story lines (Appendix 6.1). Each story line represents different demographic, social, economic, technological, and environmental developments (IPCC, 2001).

One of the major problems in applying GCM projections to basin or watershed impact assessments is the coarse spatial scale of the gridded estimates in relation to many of the exposure units being studied. Several methods have been adopted for developing regional or watershed at a sub-grid scale, a procedure variously known as “regionalization” or "downscaling" (Giorgi et al., 2001). There are two possibilities for down-scaling the GCM outputs: (a) Model-based (dynamical downscaling): nesting a finer-scale Regional Climate

Model (RCM) within the GCM. This is a rather resource intensive approach and (b) Empirical (statistical downscaling): identifying relationships using observations of large-scale and regional climatic systems (Goodess et al., 2000).

Gosain, et al. (2006) used the GCM model HadRM2 together with the hydrological model SWAT to project the impact climate change scenario on the spatio-temporal water availability in two Indian river basins. Jha *et al.* (2004) employed RCM coupled with a hydrologic model, SWAT to evaluate the impact of climate change on stream flow in the Upper Mississippi River Basin. They quantified potential impacts of climate change on water yield and other hydrologic budget components by driving SWAT2005 with current and future scenario climates. Lejalem (2006) used SWAT2005 coupled with downscaling to study climate change impact on Lake Ziway watershed water availability in Ethiopia. He estimated that the average annual precipitation in the watershed might increase up to 9.4%, average annual maximum and minimum temperatures might rise up to 1.95°C and 2°C respectively.

6.3 Methodology

6.3.1 Simulating Impacts of LUCC on Hydrological Regimes: Status Quo

Simulating the impacts of LUCC and land management practices on hydrological regime is one of the most significant parts of this research and it requires an improved procedure to instrument watersheds based on the hydrological sensitivity due to LUCC. SWAT2005 for the simulation of these impacts in Hare watershed requires analysis of spatial-temporal interaction and variations of different hydrological processes in relation to land use and land cover. For instance, variability in streamflow produced by complex interactions of land use and land cover, land management, and climate combined with competing and increased demand, makes management of water resources at watershed scales extremely challenging. However, if multiple land use and land cover maps are available, a relative assessment of the impacts of LUCC as a function of time can be accomplished taking what if scenarios.

As discussed in Chapter 3, Hare watershed has experienced LUCCs during the past four decades. There was high conversion of forest lands to agricultural and settlement land class during the study periods considered. Moreover, the high population growth has caused pressure on the land and water resources. On the other hand, there exist an irrigation project at the downstream reach that consists of three diversions structures; a modern diversion structure with traditional delivery systems (143 ha), fully traditional inundation canal diversion (744.60 ha), and fully modernized irrigation system (1336 ha). In additions, farmers are highly attracted to small scale irrigation to grow cash crops in the upper and middle part of the watershed. Therefore, there is high competition for irrigation water use among the upstream and downstream water users. Hence it is very important to investigate the impacts of upstream land use and land cover modifications on the downstream irrigation scheme and accommodate the analysis with irrigation water allocation strategy.

To accommodate these situations, streamflow simulations were made and analysed using SWAT2005 under current conditions using the 2004 land use and land cover map and under 'what if scenario' of the 1975 land use and land cover continues till the present time. Two independent simulation runs were conducted on a monthly and yearly basis using both land use and land cover maps for the period of 1992-2004 keeping other input parameters unchanged. Seasonal streamflow variability due to the LUCC was assessed and comparisons were made on surface runoff, lateral flow and ground water flow contributions to streamflow based on the two simulation outputs. Furthermore, the impact of LUCC on the existing downstream irrigation project that has a command area 2224 ha was also assessed. Results are discussed in section 6.4.

6.3.2 Future Climate Change Scenarios

Global Circulation Models (GCMs) at different resolution and complexity serve as the major source of information for constructing climate change scenarios. In order to assess the implications of future changes in the environment, society and economy on an exposure unit, it is first necessary to have information about the present-day or recent conditions as a reference point or baseline. When using GCM results for scenario construction, the baseline period serves as the reference period from which the modeled future change in climate is calculated. Most impact assessments seek to determine the effect of climate change with respect to the present, and therefore recent baseline periods from 1980 to 2001 was selected to represent baseline period for this study.

Among the different GCMs, the HadCM3 that couples Atmosphere–Ocean General Circulation Model was selected in this study for the prediction and rate of change of future climate. It is selected due to the availability of a downscaling model with sufficient details on predictor files representing the study area. Details of HadCM3 model are available in Gordon et al. (2000) and Pope et al. (2000). The climate change scenarios projected using A2 and B2 storylines are selected as the climate change forecast for the period 2010–2099. Though, three ensemble members (a, b, and c) are available for each of these emission scenarios, which refer to a different initial point of climate perturbation along the control run (Hanson *et al.*2004), data were available only for the "a" ensembles and hence only the A2a and B2a scenarios were considered. After selecting the scenarios, the future time scales from the year 2010 until 2099 were divided into three periods of 25 years and their respective changes in rainfall and temperature were determined from the base period values

The coarse spatial resolution of the GCM led to apply a downscaling model so as to downscale its outputs to suit the study area, Hare watershed. The Statistical DownScaling Model (SDSM) version 4.1 that is a windows-based decision support tool for regional and local scale climate change impact assessments was selected for this purpose (Wilby et al., 2007). SDSM is best categorized as a hybrid of the stochastic weather generator and regression-based downscaling methods. The stochastic element is used to inflate the variance of downscaled output to better agree with the observed daily data, and to generate ensembles of climate time series that differ in their individual time evolution, inter-annual means and variance. The SDSM rely on empirical relationships between local-scale "predictands" and regional-scale "predictors" to downscale GCM scenarios. Compared to other downscaling methods, the statistical method is computationally inexpensive, relatively easy to use and provides station-scale climate information from GCM-scale output, which can be most needed in many climate change impact studies. Detail on the model is available at (Wilby et al., 2007).

The SDSM predictor data files for the HadCM3 model are downloaded from the Canadian Institute for Climate Studies (CICS, 2004). The predictor variables of HadCM3 are provided on a grid box by grid box basis of size 2.5° latitude x 3.75° longitude. To represent the study area, Hare watershed (average 37° 32‘ E longitude and 6° 10‘ N latitude), the data from the nearest grid box at 5°N latitude and 37.5°E longitude (X=11 & Y=33) were downloaded from CICS. The downloaded data consist of (1) NCEP_1961-2001 that contains 41 years of 26 daily observed predictor data, derived from the National Centre for Environmental Prediction (NCEP) re-analyzes, normalized over the complete 1961-1990 period; (2) H3A2a_1961-2099 and (3) H3B2a_1961-2099, the last two contain 139 years of 26 daily GCM predictor data, derived from the HadCM3 A2a and HadCM3 B2a experiment respectively, which is normalized over the 1961-1990 period. List of the predictor variables downloaded from CICS are presented in Appendix 6.2.

The standard technical procedures provided by Wilby et al (2007) for quality control and data transformation, selection of downscaling predictor variables, model calibration, weather generator and validation were followed to generate scenarios. Historical records available on rainfall, maximum and minimum temperatures at Arba Minch, Chencha, and Mirab Abaya stations for the period from 1980 to 1990 were used for model calibration and data for the remaining period 1991 to 2001 was used for validation purposes. An empirical relationship between the predictand variables (minimum temperature, maximum temperature, and rainfall) collected from stations and the predictor variables obtained from the NCEP re-analysis data for the current climate were established to identify appropriate predictor variables that have strong correlation with the predictand variable. These empirical predictor-predictand relationships of the observed climate to downscale ensembles of the same local variables was performed with the utmost care as the behavior of the future climate scenario completely depends on the type of the predictors selected.

6.3.3 Land Use Change/Modification Scenarios

The need to develop future LUCC scenarios stems from the important role that human activities play in Hare watershed. The process of building a scenario is the creation of a new digital map of land uses, based on the one that depicts the present state of land cover in the watershed. The scenarios are mainly focused on the most likely changes that can occur in the near future. This is employed by changing percentage of one land use and land cover class in to another based on the pre-defined criteria. Accordingly, three LUCC and land management practices scenarios were constructed. All of them are focused on local issues to evaluate the consequences of different hypothetical agricultural land management practices that could have impacts on streamflow and future agricultural production. However, changes in soil management practices could have also impacts on streamflow but not considered in this research. A brief description of each scenario is given below.

Scenario 1: Continuation of Current Practices (No Interventions)

This scenario speculates the continuation of existing traditional agricultural production and assumes there will not be any intervention in any part of the watershed. Although this scenario is impractical due to the ongoing small scale irrigation interventions and human activities in the watershed, it offers a reference point when interpreting the hydrological implications of other management scenarios. Therefore this scenario acts as a base when evaluating the performance of the other two alternative management strategies.

Scenario 2: Only Small Scale Irrigation (SSI) Intervention

This scenario considers the ongoing two small scale irrigation projects intervention in the upper and middle reach of the watershed. The implementation of these new irrigation schemes is hypothesized to have impact on downstream irrigation water users and causes water shortage. A decrease in irrigation water quantity causes a decrease in cropping intensity and cultivated area and consequently results in a reduction of total income and affects the subsistence of the farmers' life downstream that by large are dependent on the water availability in Hare River. Some researchers elsewhere (Abu-Thallam, 2003) showed that a decrease of water supply by 20% will be followed by a reduction in the total cultivated area by about 14% and will lead to a decrease in the total net income generated by 15 % .

Scenario 3: SSI intervention together with Afforestation and Conservation Practices

According to this scenario, the small scale irrigation scenario is considered together with afforestation of lands having slopes greater that 45 % and terracing lands having slopes less than 30 %. This scenario will decrease mostly the grass land and some agricultural land classes through plantation in to forest land class. This scenario can be considered as best management practices in which all possible scenarios are integrated and their cumulative impact is analysed. Generally, in this land use change scenarios more focus is given to the small scale irrigation intervention with an objective to identify the impacts of these interventions on downstream irrigation project and consequently develop an optimization tool for irrigation water allocation and use that is discussed in detail in Chapter 7.

6.4 Result and Discussion

6.4.1 Impacts of LUCC on Streamflow and Irrigation Water Use: Existing situation

One of the most significant parts of the study was to evaluate the hydrological response of Hare watershed to LUCC. The evaluation was done in terms of the impacts of LUCC on the water yield near the outlet and variations in the components of the streamflow including surface runoff, groundwater flow and lateral flow. LUCC has a great influence on the rainfall-runoff process, particularly for a complex terrain, as for instance the study area Hare Watershed.

After calibrating and validating the model using the two land use and land cover maps for their respective periods (1981-1990 and 1992-2003), SWAT2005 was executed using the 1975 and 2004 land use and land cover maps for the periods and 1992-2004 while setting all the other set of input variables similar for both simulations in order to quantify the variability of streamflow due to the land use and land cover changes. This gave river discharge outputs that correspond to both land use and land cover patterns. These outputs were then compared and percentages of discharge change during the wet and dry seasons were assessed at watershed and sub-watershed levels and used as indicators to estimate the hydrological effects due to land use and land cover change. Table 6.1 presents the population density, increase in farmlands and settlements land use and land cover class and mean monthly wet and dry season streamflow variability for selected sub-watersheds.

Table 6.1 Mean monthly wet and dry season streamflow variability (1992-2004)

Selected sub-watersheds	Population density (person/km2)	Farmland & settlement class change (%)	Mean monthly flow change (%)	
			Wet season (Mar.-May)	Dry season (Nov.-Feb.)
7	285	+ 5.1	+ 7.1	- 13.8
11	250	+ 12.8	+ 8.1	- 26.9
6	329	+ 18.2	+ 11.6	- 31.8
3	386	+ 18.8	+ 13.3	- 39.6
5	386	+ 18.9	+ 11,7	- 43,3
Entire WS	300	**+ 10.4**	**+ 12.5**	**-30.5**

The result on the streamflow variability indicated that mean monthly discharge for wet months had increased by 12.5% while in the dry season decreased by 30.5% during the 1992-2004 periods due to the LUCC. Streamflow from sub-watersheds where population density is higher (386 person/km^2) and high agricultural land expansions observed (18.9%), mean monthly increase of streamflow of up to 13.3% % (Sub-watershed 3) was observed from wet period and reduction up to 43.3% (sub-watershed 5) during the dry period. On the other hand, sub-watershed 7, where farmland expansion was minimum (+ 5.1%) and population density is relatively small (285 persons/km^2), streamflow was increased by 7.1% and reduced by 13.8% during the wet and dry seasons respectively. When compared, wet season streamflow is less sensitive than dry season flow due to the reason that ground water contribution during the dry season was reduced because of less infiltration that largely caused less vegetation cover.

For assessing change in contribution of streamflow components due to LUCC, analyses were made on Surface runoff (SURQ), Ground water flow (GWQ) and Lateral flow (LATQ). The SURQ, GWQ and LATQ components of the stream simulated using the 1975 land use and land cover map for the same period were 39%, 49% and 12% while using the 2004 land use and land cover map were 44%, 42% and 14% respectively. The contribution of surface runoff has increased from 39% to 44% due to the LUCC occurred between the period 1975 to 2004. An example of these changes due to LUCC for the month May, 2000 is given in Figure 6.1.

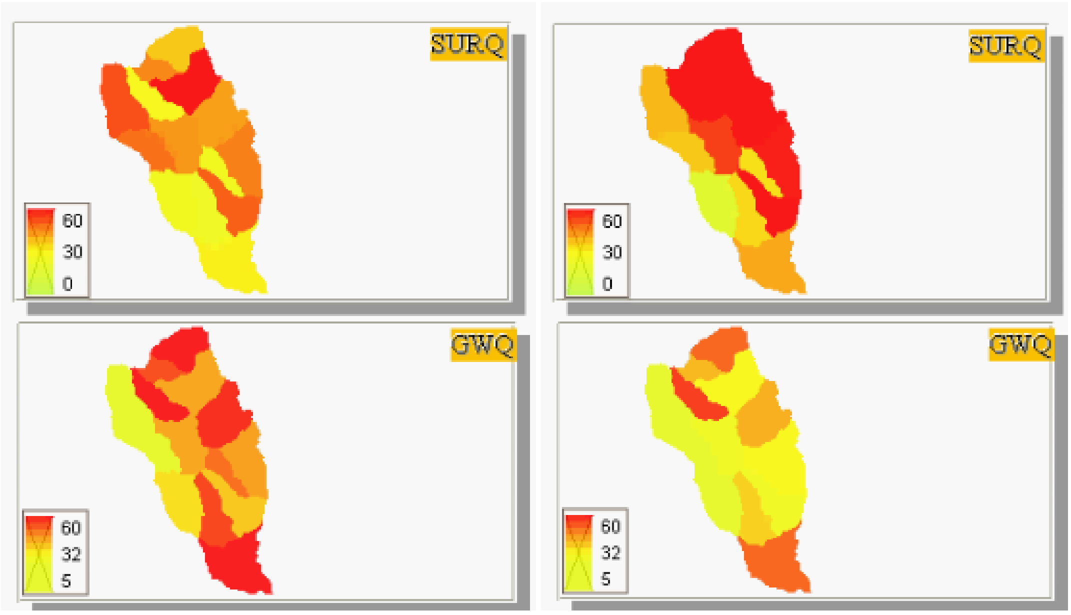


Figure 6.1 Simulated SURQ and GWQ using (a) 1975 and (b) 2004 land use maps

On the other hand, ground water flow has decreased from 49% to 42% due to the same reason. This is directly attributed by the expansion of agricultural land over forest that results in the increase of surface runoff following rainfall events and causes variation in soil moisture condition and groundwater storage. This expansion also results in the reduction of water infiltrating into the ground and supplying the shallow aquifer. Therefore, discharge during the dry months (which mostly comes from baseflow) decreases, whereas discharge during the wet months increases. These results demonstrate that changes in land use and land cover have significant effects on infiltration rates, on the water retention capacity of soils, on sub-surface transmissivity and thus on the runoff production.

All the components of the streamflow are predicted separately for each hydrological response unit (HRU) and routed to obtain their respective total amounts for the watershed, which increases the accuracy of streamflow predictions and provides a much better physical description of the water balance. Figure 6.2 provides the variation in streamflow due to LUUC over the months.

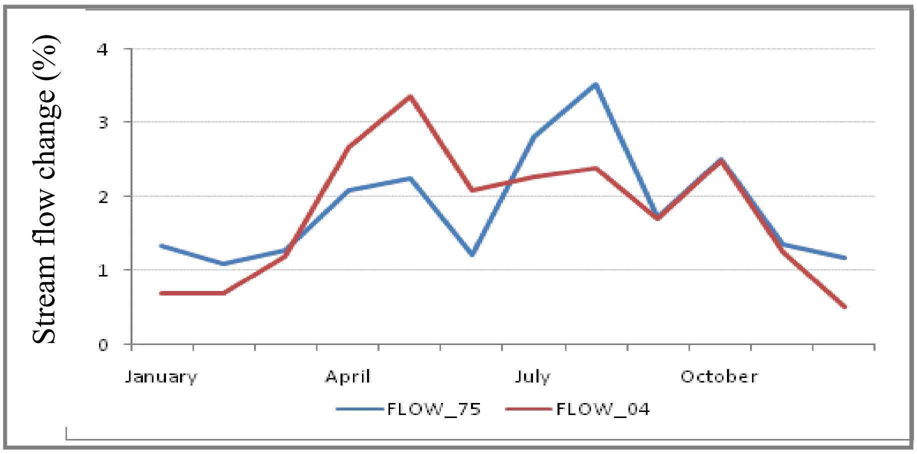
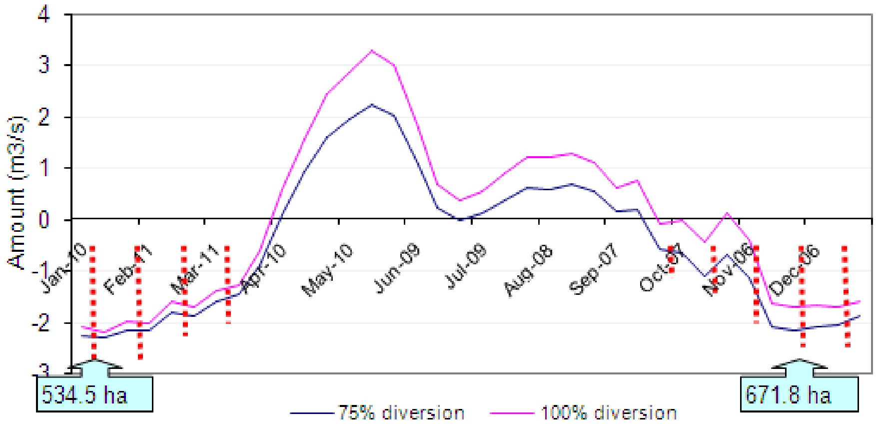


Figure 6.2 Mean monthly streamflow change due t LUCC

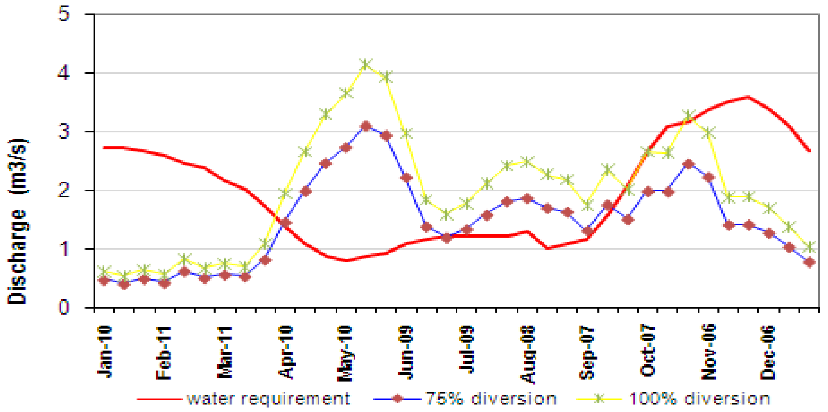
Figure 6.2 indicates that there is an immediate response to rainfall due to the decrease in land cover from 1975 to 2004 and runoff peaks shifted from August to May. This is due to the reason that forest litter has a great influence on overland runoff by absorbing rainfall and decreasing overland runoff that increase soil water storage.

Generally, the result of the analysis indicated that change of land use and land cover pattern has altered the rainfall-runoff relationship and contributed to an increase in runoff in the wet season. As explained in section 6.3.1, all input parameters (including climatic, soil, etc) were kept unchanged during the simulations so that only the impacts of LUCC are recognized. It also identified that one of the most important concerns regarding forest to farmland land use change relates to water availability during the dry season that reduced the contribution of ground water flow. Further analysis streamflow data revealed that measured annual streamflow has decreased at a rate of 7.4mm per annum while rainfall has increased at a rate of 19.8mm and 6.1mm per annum at Chencha and Arba Minch stations respectively.

The next step was to consider the effect of LUCC on the existing downstream irrigation project. Land cover effects on hydrology can largely be attributed to changes in water use throughout the year, and specifically during the dry seasons where irrigation water demands are at their peaks. Under the current set of model parameters, the result of the simulation demonstrated that that increased croplands in the upper watershed caused a reduction on dry-season flows that has direct relation to the water demand during this period. Figure 6.3 presents a decadal irrigation water demand of the downstream irrigation project and water availability at Hare River with two options.



(a)



(b)

Figure 6.3 Irrigation water (a) surplus and deficit periods and (b) Irrigation water demand compared to water availability

The impact of the LUCC on the magnitude of downstream streamflow flow behavior has already caused conflict among the irrigation water users. Streamflow analysis presented in Figure 6.3 illustrates that Hare River can irrigate only 534.5 ha, which is 24.0% of potential, even with 100% diversion during the dry season. On the other hand, it also presents that there is a remarkable amount of surplus (263%) of water during the wet period that can be reserved for the dry season.

6.4.2 Climate Change Scenario Analysis

In this section, future climate change scenarios analyses were carried out and their implications on the hydrological regime were assessed in the subsequent sections. The climate change scenarios used in this study were based on the two marker storylines (A2a and B2a) of the IPCC- SRES generated from the HadCM3 results. The SRES storylines are a global framework of possible future developments during the 21st century (IPCC, 2001). The fact that this research aims at the hydrological response to LUCCs, climate change scenarios are used to generate future climatic input data for the SWAT2005 model, thus details of how and why climate could change are not discussed. Nevertheless, some preliminary analyses were made to get an insight on the trend of future climate change. The modelling of climate involves a number of uncertainties as the understanding of the entire climate system with all relevant processes is incomplete. Furthermore, climate models cannot possibly account for every process at the very smallest scales explicitly.

To get an impression of how well the models describe future rainfall and temperature, a baseline of weather condition (1980–2001) was established to control the future scenarios. Analysis was carried out on annual base that provides the predictor-predictand relationship all along the months of the year. To test the significance of the predictor-predictand relationship, a significance level $p<0.05$ was set. Then, the model was calibrated for the period 1980-1990 at a monthly model type in order to see the monthly variations. The conditional and non-conditional processes were selected for daily rainfall, and daily temperature (maximum and minimum) values respectively. The result of the weather generator was used to validate the calibrated model using independent observed data not used during the calibration procedure and the synthesized artificial weather time series data representing the present condition. Ten years of simulation from 1991-2001 was used to validate the model.

The regression weights produced during the calibration process were applied to the time series outputs of the HadCM3 model. Twenty ensembles of synthetic daily time series data were produced for each of the A2a and B2a scenarios for a period of 1961-2099. Rainfall downscaling is necessarily more problematic than temperature downscaling, because daily precipitation amounts at individual sites are relatively poorly resolved by regional–scale predictors, and because precipitation is a conditional process. To preserve inter variable relationships, the ensemble means were used for further analysis. Table 6.2 shows the screened predictor variables that gave good correlations and model type used to predict future rainfall and temperature scenarios from the GCM outputs using SDSM.

Table 6.2 Predictor variables identified and model type used to predict future rainfall and temperature for Hare Watershed

Model	*Daily rainfall*	*Daily min. and max. Temperatures*
Predictors	• Mean sea level pressure • Relative humidity at 500 hPa • 850 hpa zonal velocity • Near surface relative humidity	• 500 hPa *zonal velocity* • Near surface specific humidity • *Mean temperature at 2m*
Model type	• Daily • Fourth root transformation • Conditional process	• Daily • Liner model • Unconditional process

Four predictor variables were identified for rainfall (Table 6.2) using daily model with a fourth root transformation of the predictand. On the other hand, three predictor variables were identified for each of maximum and minimum temperature while a linear modeling and unconditional process is specified for temperature. With these specifications, the weather generator was used to downscale observed (NCEP) predictors, and scenario generator to downscale GCM (HadCM3) predictors representing the present climate.

The series downscaled from the NCEP predictors provide an opportunity to evaluate the performance of the SDSM models in comparison with the observed rainfall and temperature data. Each series is accumulated into monthly totals and averaged over the twenty ensembles and then compared with the observed rainfall series by correlation coefficient (R^2) (Figures 6.4 and 6.5). Comparison was performed over the period of SDSM calibration and the independent verification period.

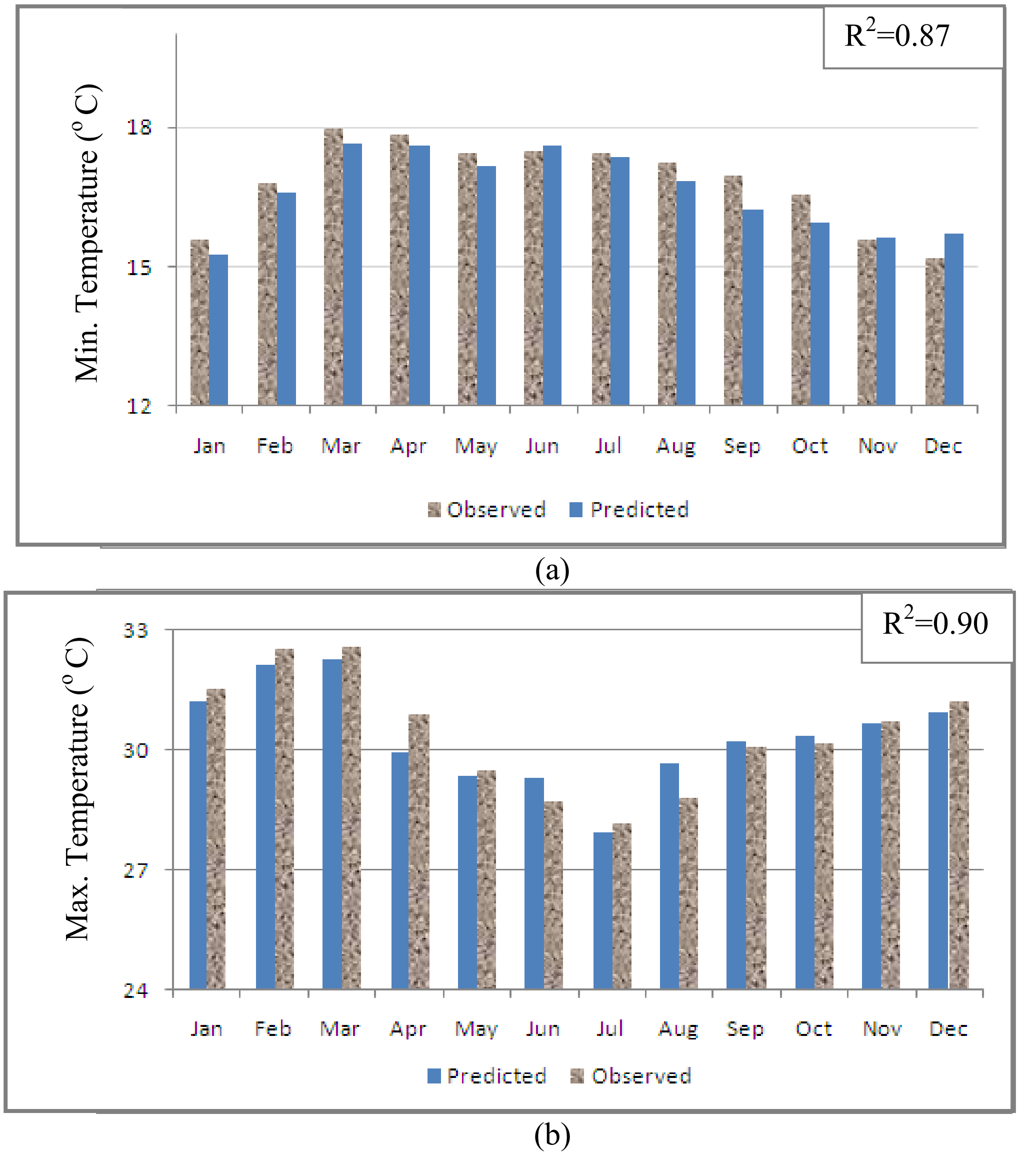
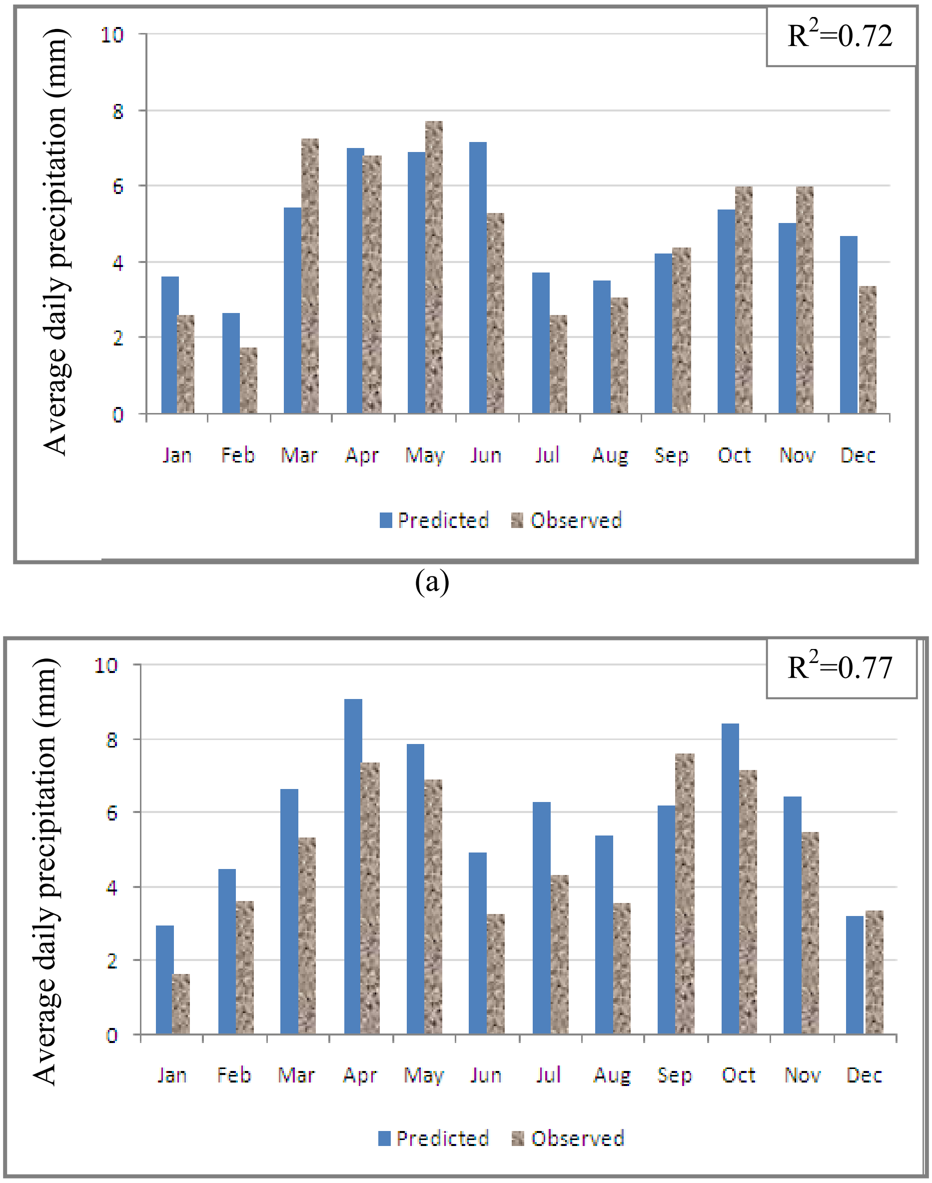


Figure 6.4 Comparison of observed and predicted mean (a) minimum and (b) maximum monthly temperatures for the period 1991-2001 at Arba Minch station

Results indicate that the models replicate observed inter-monthly and inter-annual variability faithfully, achieving correlations of the order of 0.87 for temperature (Figure 6.4) and 0.70 for rainfall (Figure 6.5) leaving residuals whose variance is much less than the variance of the raw data. The performance of the SDSM is almost as good over the verification period as it is over the calibration period, indicating that the empirical model has not been over-fit to the data. Moreover, calibration and validation of maximum and minimum temperature result show better correlation coefficient as compared to rainfall.



(a)

(b)

Figure 6.5 Comparisons of observed and predicted average daily precipitation at (a) Arba Minch and (b) Chencha stations

Consequently, the Scenario Generator operation was implemented using the identified predictors to generate future rainfall, maximum and minimum temperature data for the period of 2010-2099. The generated future scenarios for mean annual rainfall maximum and minimum temperatures are given in Table 6.3.

Table 6.3 Mean annual predicted values and relative changes of rainfall at Hare watershed

Site	***Scenario***	***Base line (1980-01)***	***2006-35 (mm)***	***2036-2065 (mm)***	***2066-95 (mm)***	***Change (%)***
Arba Minch	A2a	890	927	980	1010	12
	B2a	890	921	961	988	10
Chencha	A2a	1433	1646	1700	1731	17
	B2a	1433	1494	1551	1620	13
Mirab Abaya	A2a	745	820	871	963	22
	B2a	745	835	858	934	20

These predicted values generally show an increasing trend with respect to the base line period (1980-2001). The results above show that an increase of rainfall within a range of 10% to 22% at the three stations, minimum percentage of change (10% with B2a scenario) relative to the baseline is at Arba Minch whereas maximum change being at Mirab Abaya (22% with A2a scenario).

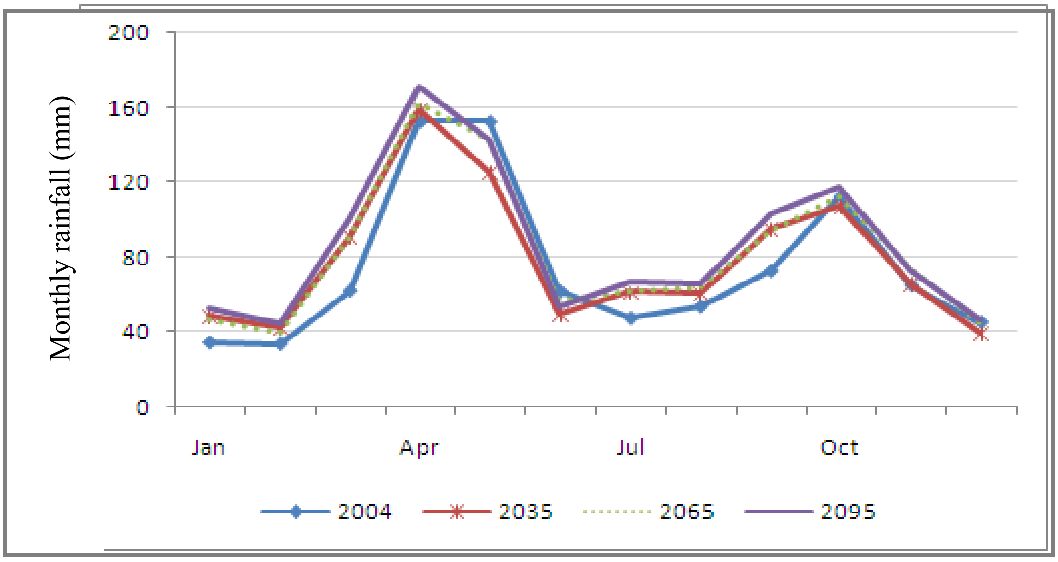


Figure 6.6 Predicted precipitations for Arba Minch station on monthly bases using A2a scenario

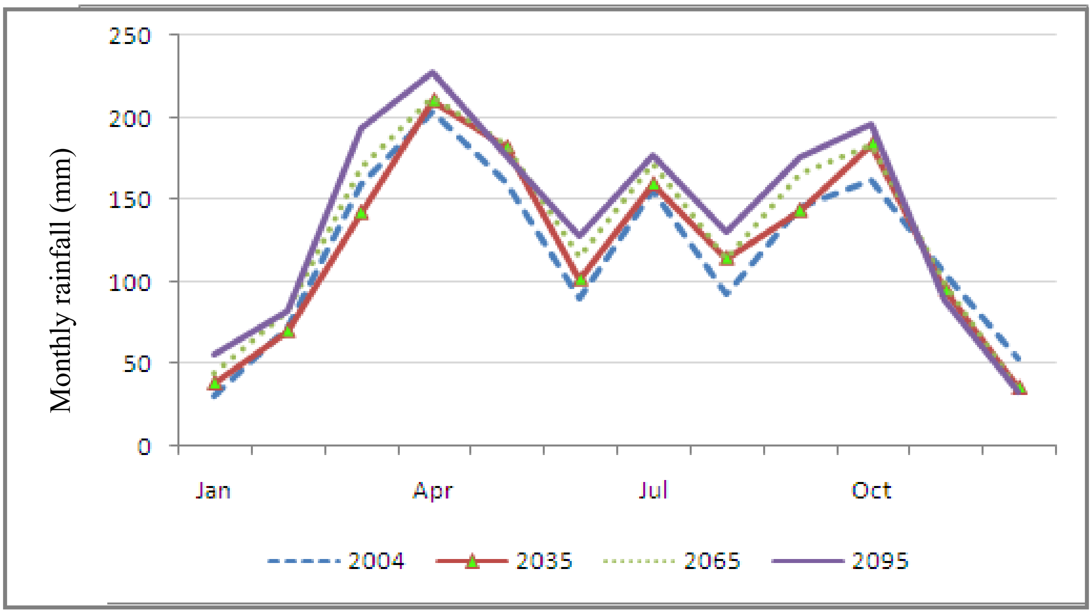


Figure 6.7 Predicted precipitations for Chencha station on monthly bases using A2a scenario

Figures 6.6 and 6.7 presents the predicted mean monthly rainfall at Arba Minch and Chencha stations using A2a scenario for the periods 1980-2004, 2010-2035, 2036-2065 and 2066-2095. There is a similar trend in increase of precipitation at the two stations in the coming 100 years. The increase in rainfall during the wet season for the first two periods (2035 and 2065) is not significant as that of the last period (2095). However, there is a significant increase in rainfall during the rest months during the whole simulation periods.

On the other hand, Figure 6.8 illustrates the predicted annual rainfall with A2a and B2a scenarios for the period of 1980-2099. Here also, the trend of annual of rainfall generated for future climate scenario suggests a continuous increase in rainfall for the coming decades. It can be seen from the Figure that both scenarios predicted future rainfall in a similar trend and the variation in predicted rainfall using the two scenarios not as such significant.

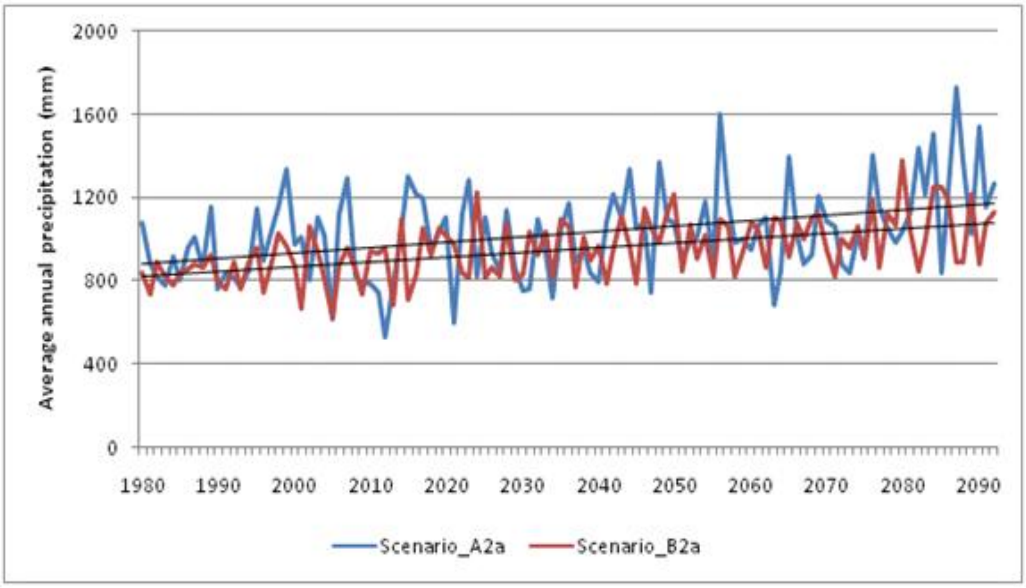


Figure 6.8 Predicted A2a scenario and B2a scenarios precipitations on yearly bases for Arba Minch station

Similarly, scenario analysis on monthly maximum and minimum temperatures with both A2a and B2a scenarios reveals that maximum and minimum temperatures will increase in the coming 100 years by an average of 2.2 ^{0}c and 1.8 ^{0}c respectively when compared to the base line. When comparing rainfall from the two climate change scenarios, larger differences between the three sites than the differences between the scenarios are detected in terms of both absolute and relative changes. This means that the statistical downscaling of the HadAm3 model with emission scenario A2a shows a similar range as obtained with the B2a emission scenario, only the A2a scenario is used for further analysis.

6.4.3 LUCC Scenario Analysis

This section discusses future land use and cover change scenarios analysis carried out and their implications on the hydrological regime. The output of climate change scenario analysis in the previous section was utilized as weather data in for the SWAT2005 model. During the scenario analysis, more focus was given to the impacts of small scale irrigation interventions in the upper and middle reach of the watershed. Since it is expected that both land use and land cover and climatic change will result in a diversity of environmental responses, hydrologic variables other than streamflow, are also included in this analysis. Based on the land use and land cover, and climate change scenarios, impacts of these changes together with small scale irrigation intervention are simulated using the SWAT2005 model.

In order to assess the effects of the land use changes developed through the three scenarios, SWAT2005 model was run using the climate change scenarios independently for each cases while keeping other set of parameters unchanged. The execution of the model gave river discharge outputs that correspond to the three scenarios. These outputs were then compared to the ones of the base run, thus estimating the percentages of discharge change for every scenario.

Although climatic data for the period of 2010-2099 was generated, land use change scenario analysis was carried out for the first period (2010-2035) in order to maintain consistency with the application of the irrigation water allocation tool that enable direct comparisons between the streamflow changes. Operation application of a hydrological model often requires the prediction of streamflow in (future) time periods without streamflow observation data. Data for a case specific optimization of model parameters are not available for such applications, so some parameters have to be generated and others have to be derived from baseline time period. Therefore, future changes in river streamflow were calculated with respect to the baseline period (1980–2004).

Scenario 1: Current practices scenario

The mean monthly values for the percentage of change in total streamflow for the coming 25 years of simulation are plotted in Figure 6.9. As presented in Figure 6.9, an increase in streamflow is observed during wet months and a reduction during dry ones. The results from the climate change scenarios with the A2a emission scenario indicates that a fluctuation in change of streamflow between -4.5% (decrease) to +12.5% (increase) with an overall average increase in the mean annual streamflow of 3.6 % per decade if there is no management intervention. Increases for wet months are in the range 6.1%, while during the dry season decreases by a percentage of 3.4%. This output can be interpreted by nothing but the predicted increase in rainfall values in future and less infiltration during the wet season due to the agricultural and pasture land use systems. This implies that the existing land use and land cover system results in the reduction of water infiltrating into the ground and supplying the shallow aquifer. Therefore, discharge during the dry months (which mostly comes from baseflow) decreases, whereas discharge during the wet months increases.

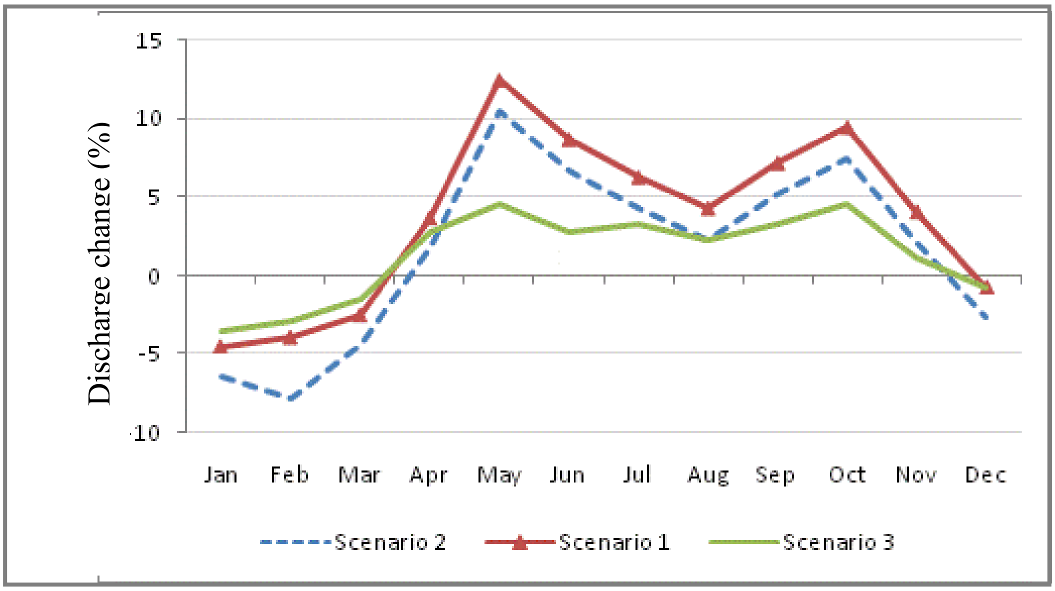


Figure 6.9 Change in mean monthly discharge (%) for the three scenarios for the period 2010-2035 as compared to the base line

Scenario 2: Only small scale intervention scenario

The results of this scenario is different to that the first scenario. As shown in Figure 6.9, the percentage change in streamflow fluctuates between -7.9% (decrease) to +10.5% (increase) the range of which indicates further reduction during the dry season as compared to the first scenario. Similarly, the stream flow during the wet season was reduced by 2.4% as compared to the first scenario. However, the trends of the two graphs are similar despite the value difference at each month. The reduction in streamflow during the dry season can be explained by taking into consideration the full abstraction of streamflow (without optimization) for irrigation purpose in the upper and middle reach of the watershed. When the two irrigation schemes are implemented, the streamflow at the downstream would be reduced.

Scenario 3: Best management scenario

The results had a pattern different from the first two scenarios. As shown in Figure 6.9, the percentage of change of streamflow when compared to the base period was increased to -3.5% during the dry season while reduced (+4.5%) during the wet season. This could be due the integrated impacts of the abstraction of water for irrigation in the upper and middle reach, the reduced slope due to conservation and afforestation can be explained by taking into consideration the abstraction of excess runoff during the rainy season and application of irrigation water during the dry season. When comparing the second scenario, there will be an increase in streamflow during the dry season since the fluctuation in percentage change was increased from -7.9% to -3.5 during this season. This can be explained by the reduction during the wet season due the implementation of conservation and afforestation activities will reduce the surface runoff during the wet season and consequently groundwater contribution during the dry season will increase. As a result of this, the variation in streamflow is very small among the months from April-October unlike the other two scenarios.

Table 6.4 present the contribution of Surface Runoff (SURQ), and Ground Water flow to the streamflow (WYLD) simulated using SWAT2005 during the months dry (January), main rainy month (May), between the two rainy seasons (August) and the second rainy month (October) with their respective rainfall (PREC) using scenario 3 .

Table 6.4 Contributions of SURQ and GWQ to WYLD for selected sub-watersheds of Hare watershed

Sample Sub-watershed	Parameters (mm)	January	May	August	October
	PREC	30.6	176.4	121.3	456.1
1	SURQ	0	11.97	13.2	146.8
	GWQ	2.1	37.7	117.4	100.1
	WLYD	2.3	54.4	137.7	259.1
4	SURQ	0	44.7	11.2	142.8
	GWQ	2.0	71.9	111.6	95.6
	WLYD	2.6	132.1	137.7	256.9
10	SURQ	0	64.6	20.1	181.1
	GWQ	1.7	66.2	100.1	82.2
	WLYD	2.1	144.2	129.8	282.4

Figures 6.10 to 6.13 below illustrate the same result for better understanding of the spatial distribution of the streamflow components at each sub-watershed during each of the months.

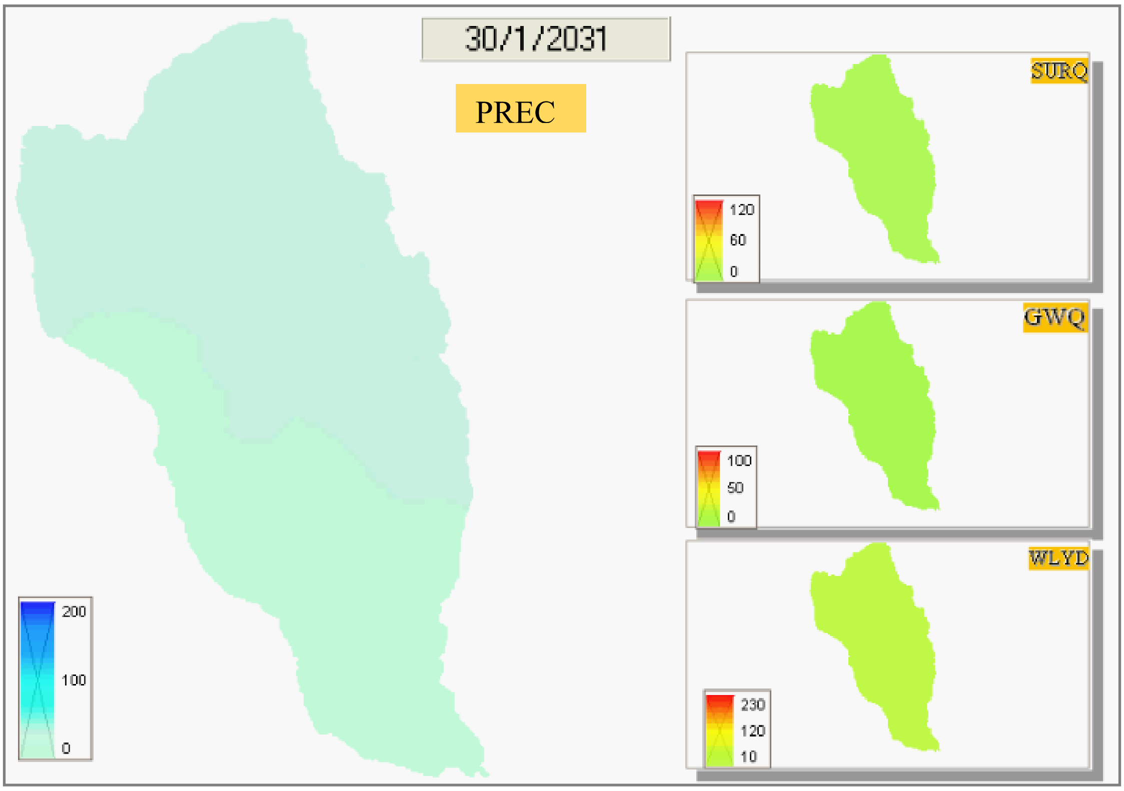


Figure 6.10 Contribution of SURQ and GWQ to WYLD for the month January, 2031

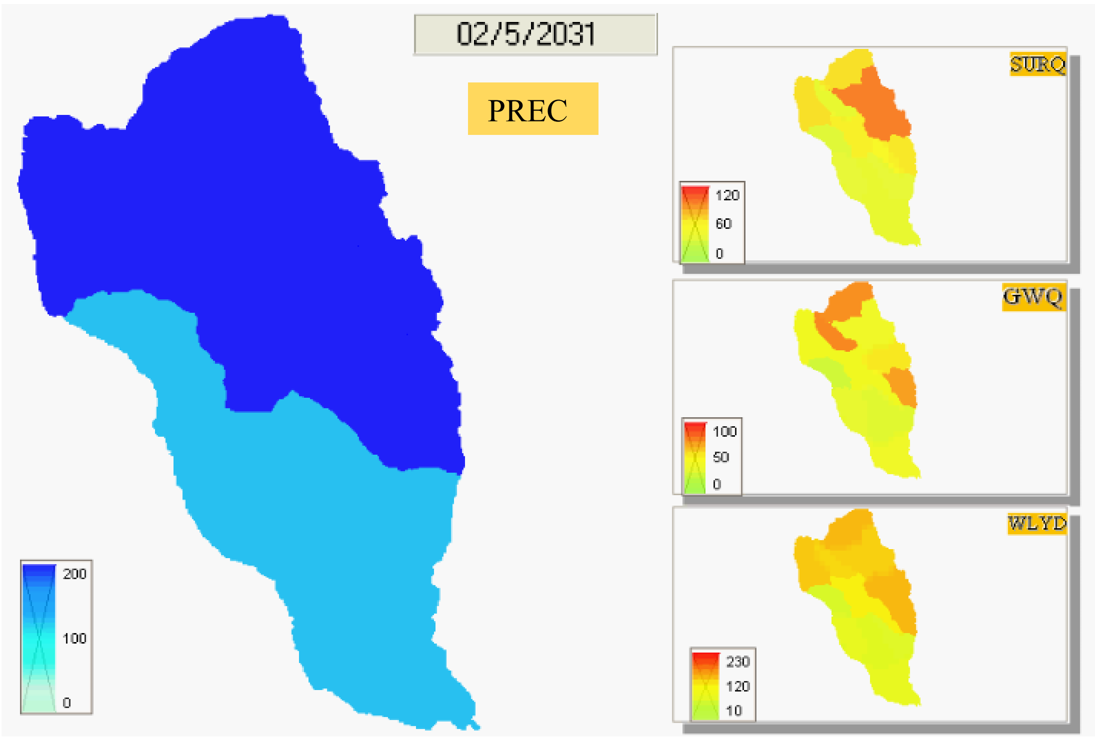


Figure 6.11 Contribution of SURQ and GWQ to WYLD for the month May, 2031

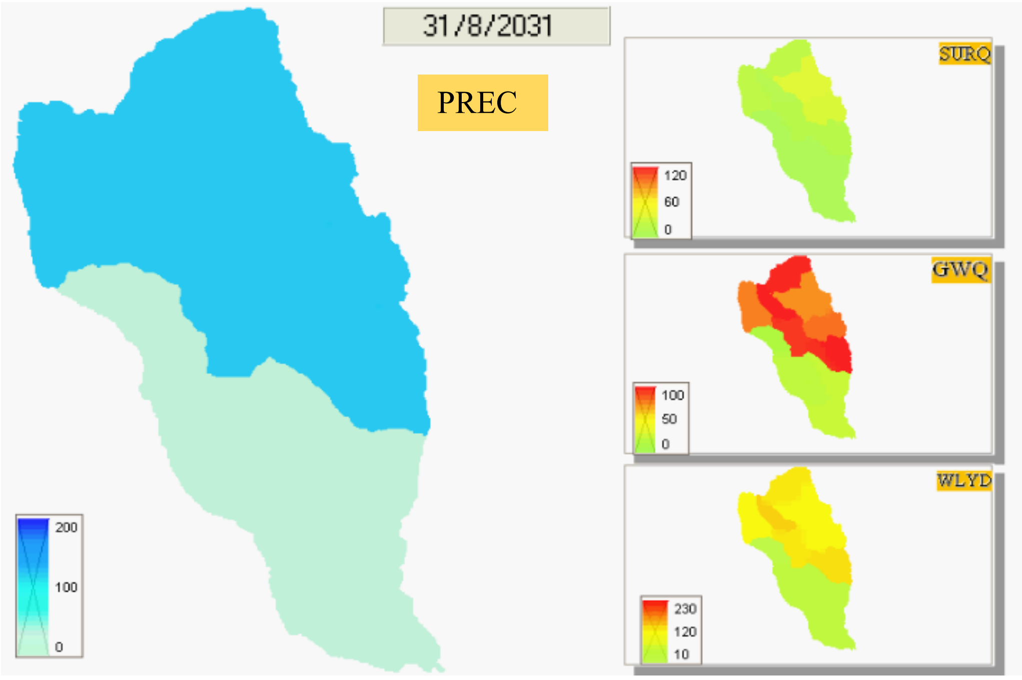


Figure 6.12 Contribution of SURQ and GWQ to WYLD for the month August, 2031

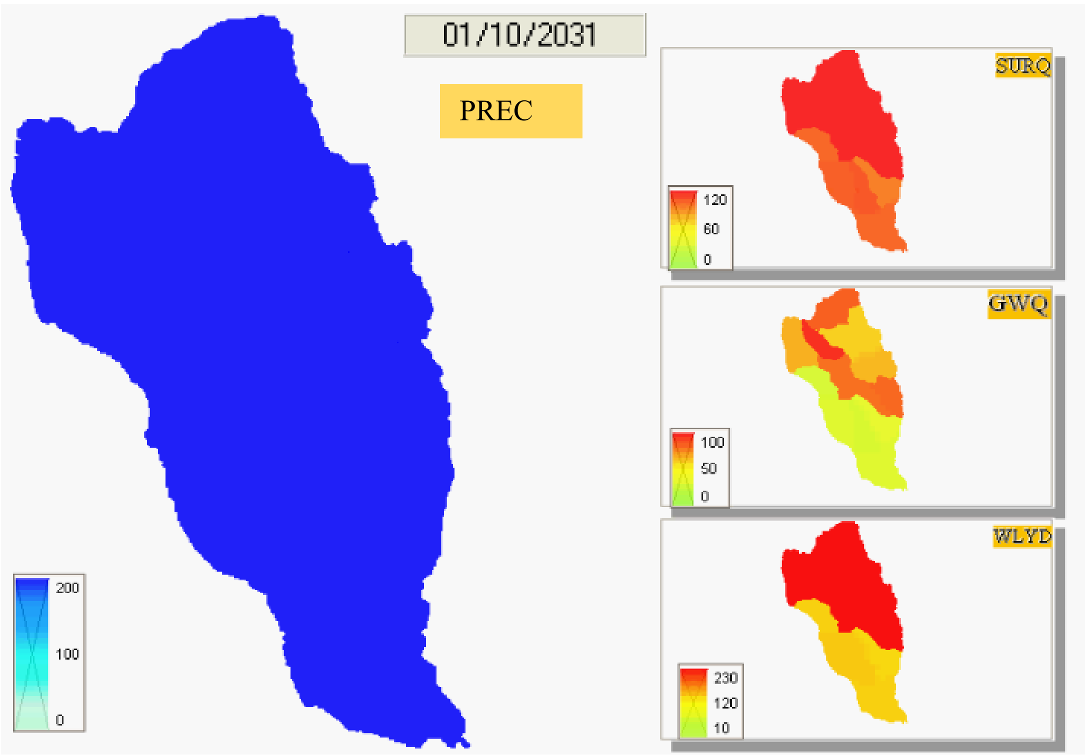


Figure 6.13 Contribution of SURQ and GWQ to WYLD for the month October, 2031

As indicated in the above Table and Figures, streamflow (water yield, WLYD) will be at its lowest point during the dry season (January). This is due to the fact that there is no contribution from surface runoff while the groundwater contribution is very small. After rainfall commences (May) WLYD will increase due to the contribution of surface runoff (SURQ) from most of the sub-watersheds. Contribution of ground water flow (GWQ) exceeds SURQ between the main and second rainy seasons (August) due to the groundwater flow delay time. For this particular year, the streamflow will have maximum WYLD for the second rainy season due to the contribution from SURQ and GWQ. Moreover, it can be observed from the Figures that substantial spatial variability of SURQ and GWQ contributions from each sub-watershed. For instance SURQ from agricultural sub-watersheds during the rainy season (May) is higher than the rest sub-watersheds. These sub-watersheds are very close to district town Chencha where high pressures exist.

Generally, the results from the three scenarios indicate that the effect of climate change in terms of the relative percentage difference is greater than that of the land use change. Climate change is, therefore, the major contributor to streamflow changes. It should be also recognized that only changes in climate and land use and land cover are considered in this study. However, changes in the physical properties of the watershed for instance modification of soil properties can also have an important implication on the hydrological regime.

6.5 Conclusions

The aim of this chapter was to investigate the hydrologic responses resulting from LUCC and climate changes at Hare watershed as case study. First simulations were made to evaluate the impacts past and present LUCC on the existing irrigation project at the downstream part of the watershed. As a result of the LUCC streamflow increased by 12.5% during the wet season and reduced by 30.5% during the dry season between the years 1992-2004. These changes in streamflow were particularly caused by the change in the forest cover to farm lands and settlements. This method of evaluating the impacts of LUCC on water availability can be used when planning for the agricultural seasons particularly for the time of higher demands of the irrigation water supply. Moreover, this method can be implemented for future land use scenarios to predict the changes that may happen to the river flow regime.

The next phase of the research was to project future impacts of climate and land use and land cover using certain possible scenarios and consequentially asses their impacts on irrigation water availability. In this study, available A2a and B2a climate scenarios on a grid box basis of size 2.5° x 3.75° for the region were downscaled to a watershed level. Analysis made using HadCM3 for the period of 2010-2099 showed that an increase in future average annual precipitation by 10-22% and average temperature by 2.1^{o}c when compared to the baseline period (1980-2001). In the process, the Statistical DownScaling Model (SDSM) was able to simulate future climatic scenarios satisfactorily with the same trend to that of the baseline period. Moreover, the performances of the model for maximum and minimum temperature results show better correlation coefficient as compared to rainfall. However, it must be noted that the climate change scenarios were based on past measurements, and as such reflect only past and current changes. It is not possible to be certain about current empirical relationships between the predictors and predictand (Table 6.2) will be also the same in future.

On the other hand, three different hypothetical land use change scenarios were considered based on the present land use configuration and possible land use trends in the study area. Accordingly, simulation were made that take in to account these scenarios to acquire valuable information on the upstream-downstream linkages with respect to water use interventions in the upland areas and resulting impact at the downstream water users. The outputs from these scenarios were compared to the baseline run. All three scenarios gave an increase in discharge during wet months, and a decrease during dry periods.

By extending the current practice without any intervention (Scenario 1), an increase in mean monthly river discharge up to 12.5% and a reduction up to -4.5% were observed during the wet and dry seasons respectively. Only small scale irrigation intervention according to Scenario 2 resulted in substantial decrease (-7.9%) in mean monthly discharge during the dry season, while during the wet season, discharge increased up to 10.5%. The final scenario gave a lower increase during the wet season (4.5%) and lower reduction in streamflow during the dry season as compared to the other two scenarios. The results thus suggest that only small scale irrigation intervention in the upper and middle reaches of the watershed without soil and water conservation and afforestation activities can reduce water availability at the downstream reach of the watershed. Moreover, it should be noted that improving soil management practices could also have impacts on seasonal streamflow.

In the analysis of future scenarios, considerable attention was given to impact of two small scale irrigation projects on the existing downstream project. Currently, the amount of streamflow available at the downstream satisfies only 24 % of the total irrigable land at the downstream irrigation project. This problem of deficit in irrigation water availability will further worsen if the new two small scale irrigation projects constructed in the upper watershed fully implemented. Thus, one of the major anticipation at the initial stage of this research was that availability for irrigation water at the downstream reach is expected to be substantially reduced even than current consumption when the two irrigation projects at the upper and middle reach of the watershed fully put into action. These ongoing upstream irrigation water abstractions should not be based on the assumption that water is a "free" good and needs correct economic approach for assessing development of water projects upstream that divert water shall consider the forgone benefits of disruption to the natural environment and reduction of water availability and impacts on economic livelihoods at downstream.

Generally, from the overall results of this chapter it can be concluded that the combined effects of changes in land use and climate could potentially change in a significant way the hydrological regime of the whole watershed. The results can have an important contribution for water resources managers to be aware of and prepared to deal with the effects of future land use and land cover and climatic change on streamflow and related variables. The analyses made on the different components of the hydrological regimes are good indications of the extent of impacts of land use and land cover and climatic change on water resources.

CHAPTER 7

Towards Sustainable Water Resource Management in the view of Land Use and Climate Changes

7.1 Introduction

This chapter uses the scenario outputs from Chapter 6. As discussed in Chapter 6, land use/ cover and climate change scenarios do have impacts on streamflow and consequently, there is deficit in irrigation water availability at the downstream reach of Hare watershed. These conditions further worsen if new Small Scale Irrigation (SSI) projects are implemented in the upper and middle reaches of the watershed. Thus, it needs an appropriate hydrologic and economic approach for assessing development of water projects upstream that consider the economic livelihoods and natural environment impacts downstream.

Fereres and Soriano (2006) discussed that irrigated agriculture is the primary user of diverted water globally and reaching a proportion that exceeds 70–80% of the total in the arid and semi-arid zones. In recent years there has been an increasing recognition for the need of a new approach to the management of land and water resources for sustainable utilization of natural resources. However, irrigated agriculture is still practiced in many areas in the world with complete disregard to basic principles of resource conservation and sustainability. Furthermore, Tanik, et al., (2003) described that an integrated approach that deal with hydrological responses to LUCC and water management problems are still in the earliest stages of development, and there are still many problems inherent in irrigation water utilization and management in particular that have not been worked out. Therefore, irrigation water management in an area of water scarcity will have to be carried out most efficiently, aiming at saving water and at maximizing its productivity.

Cai, et al., (2001) described that sustainable irrigation water management should simultaneously achieve two objectives: sustaining irrigated agriculture for food security and preserving the associated natural environment. They argued that sustainability in irrigation water management can be indicated by water supply system reliability, reversibility, and vulnerability, environmental system integrity, equity in water sharing, and economic acceptability.

Molden et al., (2003) provide how irrigation water management at farm level, irrigation system level and watershed level can be linked in three ways in order to enhance water productivity. They considered imposition of reduced water conveyances due to reduced water availability as the most common scenario where there is less water available for agriculture at system or subsystem level. In this case, the pattern of water conveyance is changed and farmers must make specific responses at farm level that will lead to increases in water productivity. In this context deficit irrigation scheduling principles can be an option in which farmers practicing irrigation farming to cope with the pressure that has been put on them to utilize irrigation water effectively and must release some water for downstream water users.

Similarly, Gorantiwar and Smout (2005) considered irrigation water management as three processes which are undertaken on an irrigation scheme: area and water allocation, operation, and evaluation. Several methodologies have been developed to prepare the allocation of irrigation water during the planning process. Depending on the objectives, the allocation plans were based on optimizing the use of land (Shyam et al.,1994; Onta et al., 1995), or water (Akhand et al., 1995; Wardlaw and Barnes, 1999; Tantawy, et al., 2007) or both land and water (Paul et al., 2000; Reca et al., 2001; Gorantiwar and Smout, 2006). In these models the land and/or water resources were optimized for obtaining maximum crop production or monetary return or for irrigating maximum land.

Furthermore, most of the water and/or land allocation models were mainly concerned with maximizing the benefits of agricultural production from the irrigation schemes (i.e., productivity) and did not address the issues of distributing the water to farmers in different irrigation schemes found in a watershed when there is limited available water. As the benefits of irrigation are widely recognized in developing countries, farmers in the command areas of irrigation schemes are concerned about getting an equitable share of water and adequate supply of water (to fill the root zone to field capacity) in addition to maximizing the net benefits. These concerns can be indicated by performance measures of equity, adequacy and productivity, respectively (Gorantiwar and Smout 2005).

In the context of Ethiopia, Awulachew (2005) depicted that poor management of agricultural water leaves almost all part of the country highly susceptible to rainfall variability which depicts itself in terms of prolonged dry spells and droughts. Furthermore, there are many empirical evidences that report poor managements of surface irrigation practices in the country. For instance, Kassa (2001) reported poor performance of surface irrigation methods at middle Awash; Checkol and Alamirew (2007) identified poor irrigation water management at Geray irrigation scheme in Northern Ethiopia; Seleshi et al., (2007) reported poor performance and managements of selected irrigation schemes from Awash Basin, Blue Nile Basin and Rift Valley. Nonetheless, Awulachew (2005) suggested that irrigation and improved agricultural water management practice could provide opportunities to cope with impact of climatic variability enhance productivity per unit of land, particularly small scale irrigation that benefits small holders.

Recently, Belete, (2007) assessed the performance of Hare irrigation project to improve system operations and assess progress against strategic goals. The studies indicated that there are even complaints among the four Kebeles that are using the downstream irrigation regarding unequal distribution of water among the users in the scheme. The problem is exacerbated when we consider that irrigation water demand is mainly during the dry periods where there are low flow conditions and when aquifer levels are at their lowest level.

Therefore, it is critical that conservative irrigation water management practices be implemented at the watershed in order to minimize the scarcity of downstream irrigation water. In addition to conservative management practices, determining the optimal level of water diversion at the irrigation sites is therefore a critical issue. As a result, there is an immediate need to help farmers to optimize their water use and the allotment of water at the three surface irrigation sites. Without this optimal water use, the exploitation of water resources may be a real threat to conflicts between the upstream and downstream water users and future development process in the watershed.

7.2 Irrigation Water Use and Management: A Watershed Perspective

A watershed inherently integrates the ‘upstream’ with the ‘downstream’ users through the flow of water as part of the general hydrological cycle. The upstream projects are usually concerned mainly with maximizing the returns to upstream irrigated agriculture. Farmers benefiting from the diverted irrigation from the upstream water projects are not anxious about any resulting impacts on downstream water availability. However, the diversion of water for upstream irrigation projects directly affects the supply of water downstream. Nevertheless, maximizing returns for the whole watershed needs assessment of all irrigation water demand and equitable allocation of available water in a coherent watershed perspective. Moreover, it needs participator planning that considers all stakeholders in the watershed. It should be however noted that water allocation is not generally an issue when stream water availability far surpasses irrigation water demand.

Consequently, the problem facing watershed planners and managers is to determine the contribution of the upstream water to the downstream agricultural system, and how this availability might change over time as more water is diverted to the upstream projects. The benefit from irrigated crops in a watershed can be improved by reducing the amount of water used and optimizing the timing of application at each irrigation site. Deficit irrigation scheduling approaches based on applying irrigation water below full crop water requirement, but aimed at increasing efficient use of the allocated irrigation water so as to give the highest crop production with the least water use, must be employed. Accordingly, models to assess impacts of alternative strategies of water allocation in irrigated river basins with water deficit problems have in the past years been developed for numerous river basins are proved to be very helpful (Kirda and Kanber, 1999b; Reca et al. 2001; Draper et al. 2003; Letcher and Jakeman, 2003).

A water supply constraint that decreases transpiration below the rate dictated by the evaporative demand of the environment is paralleled by a reduction in biomass production. Therefore, water stress is observed when actual evapotranspiration rates deviate from potential evapotranspiration rates, as a result of which crop response can be impaired. When the two are equal, available water is sufficient to meet the entire plant water demand and, as a result, plants grow at their optimal rate, thus maximizing yields for the given environmental conditions. Generally, the relationship between crop yield and applied irrigation follows a pattern of rising crop yield with increasing amounts of applied water until an optimal quantity of applied water is obtained, after which yield begins to decrease with further increases in applied water due to over saturation (Doorenbos and Kassam, 1979).

Therefore, crop yield response to different amounts of irrigation water applied, commonly known as yield production functions, are essential to decide optimum irrigation water requirement at a watershed scale. Yield production functions not only shed light for economical considerations in irrigation projects but also show agronomic response of crops to different levels of water applications. There are lots of different mathematical models to constitute for yield functions. The crop yield response factor gives an indication of whether the crop is tolerant of water stress. When this factor is greater than unity it indicates that the expected relative yield decrease for a given evapotranspiration deficit is proportionately greater than the relative decrease in evapotranspiration (Kirda *et al.*, 1999a).

The main objective of deficit irrigation is to increase water use efficiency by reducing irrigation amount that has little impact on yield. It is thus relatively a new area of interest in the agricultural industry where water supply is maintained below maximum levels allowing for mild water stress on crop species with minimal effect on crop yields. The resulting yield reduction may be small compared with the benefits gained through use of the saved water to irrigate other crops or downstream water irrigation water users. A modest and acceptable irrigation deficit level depends on the crop species and the growth stage in the life cycle of the crop in which such a deficit is suffered. This practice may result in substantial water savings, particularly in areas of water scarcity, with only minimal negative effects on crop yield. However, before implementing a deficit irrigation method, it is necessary to know crop yield responses to water stress, either during defined growth stages or throughout the whole season. It is important to consider the crop yield response factor (K_y) that varies depending on crop variety, irrigation method and management, and growth stage when deficit evapotranspiration is imposed (English and Raja, 1996; FAO, 2002; Kirda, 2002). The K_y values of for some crops are given in Appendix 7.2.

Accordingly, some results showed water savings of 23%-52% can be attained with deficit irrigation for tree crops (Kang and Zhang, 2004; Fereres and Soriano, 2006). Similar works on potato and on many other crops has demonstrated the possibility of achieving optimum crop yields under deficit irrigation practices by allowing a certain level of yield loss from a given crop with higher returns gained from the diversion of water for irrigation of other crops. The challenge of quantifying the evapotranspiration reduction affected by deficit irrigation (net water savings) remains, as direct measurements are complex (Burba and Verma, 2005), and the models used to estimate the actual evapotranspiration of stressed canopies are still quite empirical. Generally, when water supplies are limiting, the farmer's goal should be to maximize net income per unit water used rather than per land unit. Recently, emphasis has been placed on the concept of water productivity, defined here either as the yield or net income per unit of water used in evapotranspiration (Kijne et al., 2003; Zwart and Bastiaansen, 2004; Fan et al., 2005).

It must be noted that management of irrigation water should incorporate a participatory approach, which is the involvement of irrigation users in all aspects and all levels of irrigation management (World Bank, 2004) for sustainable utilization and management of water resources. However, the scope of this research is limited to the technical aspects irrigation water management particularly irrigation water allocation employing deficit irrigation principles.

7.3 Simulation-Optimization Modelling Approach for Irrigation Water Allocation

As discussed in the previous section, the traditional approach of irrigation water application attempts to attain the highest yield rather than attempting to achieve the highest productivity of water expressed as the yield per unit volume of water. Integrated simulation-optimization models are attractive tools for overcoming problems related to limited water availability and optimal use of it, as all terms of the water balance are evaluated and long-term simulations can be performed easily. In the recent years, a number of researchers have dealt with the simulation and optimization models for planning and management of irrigation (Kipkorir et al. 2001; Kuo and Liu 2003; Mishra et al. 2005) to solve problems related in such area. However, most of these models are site-specific and address local problems. Moreover, these models focus either on maintaining equity or attaining maximum benefit of the irrigation system.

In terms of model formulation and solution approaches, integrated simulation-optimization (hydrologic-economic) models can be classified into models with a compartment modeling approach and models with a holistic approach. Under the compartment approach there is a loose connection between the economic and hydrologic components, and only output data are usually transferred between the components. Under the holistic approach, there is one single unit with both components embedded in a consistent model. Information transfer between hydrologic, agronomic, and economic components remains a technical obstacle in ‘‘compartment modeling,’’ while in ‘‘holistic modeling,’’ information transfer is conducted endogenously. However, the hydrologic side in the holistic approach is often considerably simplified due to model-solving complexities (Cai et al., 2003).

Moreover, in the holistic approach, optimization is difficult, especially if irrigation water is limited, since most optimizing algorithms require that the system’s objective function and constraints be expressed analytically. Therefore, the simulation-optimization approach that makes use of an efficient search procedure to find the optimum irrigation rule under deficit irrigation conditions is preferred when there is limited water available (Kuo and Liu 2003).

Gorantiwar and Smout (2005) proposed a methodology that modifies an area and water allocation simulation–optimization approach that considers the heterogeneity of the irrigation scheme in the allocation process, and take account of equity and adequacy of supply to irrigated areas. Kuo and Liu (2003) developed an Irrigation Simulation and Planning Model via a customized genetic algorithm, which maximizes the net benefit of an irrigation system. Similarly, Sattari, et al., (2006) employed a deterministic optimization model to optimize the reservoir capacity of small irrigation scheme. Ghahraman and Sepaskhah (2002) developed an optimization model to allocate water from a single purpose reservoir to an irrigation project with pre-determined multiple cropping patterns. Many more authors have proposed semi-empirical water production functions that relate crop yields to the amount of evapotranspiration. One of the most widely used water production functions is the multiple form of Stewart formula proposed in the FAO methodology (Doorenbos and Kassam, 1979).

7.4 Methods and Procedures

7.4.1 General

Land use/cover and climate change scenarios developed in Chapter 6 are used as inputs for SWAT2005 to simulate selected scenarios for the period of 2010-2035. Among the two climate scenarios A2a was selected (section 6.4.2) while 'Best management scenario' was selected from the land use/cover change scenarios discussed in section 6.4.3. Therefore, the primary thrust of this chapter revolves around the development of an irrigation water allocation and use program for optimal crop yield production and economic benefits through deficit irrigation principles considering Hare watershed as case study. It tries to identify upstream-downstream linkages in terms of irrigation water utilization, mainly for furrow irrigation technique. Obviously, water that is diverted upstream means less water downstream, and the result is that upstream activities benefit at the expense of downstream activities.

Basically, the downstream surface irrigation project at Hare watershed is entirely dependent on the amount of water available in the Hare River. Therefore, with the intervention of the two SSI, there will a high competition for the limited water resources between farmers within the downstream irrigation project, the three irrigation sites in the watershed and between the agricultural sector and other ecological uses. A simple decision support irrigation water allocation and use program is developed to illustrate this important issue and counteract the problem at Hare watershed.

The benefit of taking an integrated approach to irrigation analysis over Hare watershed lies in integrating an irrigation water allocation and use program with the hydrological model (SWAT2005) to identify the best possible option through which farmers in the whole watershed benefit. Estimation of equity based benefits needs information on the amount of water available at each sub-watershed. For this reason, a simulation–optimization approach was employed to allocate the available water resources among competing crops and irrigation sites with more emphasis for cash crops including apple in the upper sub-watersheds.

In this research, three reservoirs that are impoundments located on the main channel network of a Hare river were designed at the diversion sites for the purpose of reducing the problem of shortage of irrigation water during the dry season. The locations of the reservoirs are identified at the existing and ongoing irrigation diversion sites. The important objective of the reservoirs designed is to conserve the excess streamflow during wet season and for promotion of effective releases of irrigation water during the dry season. A description of the design process of reservoirs in SWAT2005 modeling environment is given in Appendix 7.1.

Figure 7.1 illustrates the location of the two SSI schemes in the upper and middle reaches of the watershed (No. 2 & 3) and the existing irrigation project at the downstream reach (No. 1) and Table 7.1 presents the potential irrigable areas and crops at the three irrigation sites.

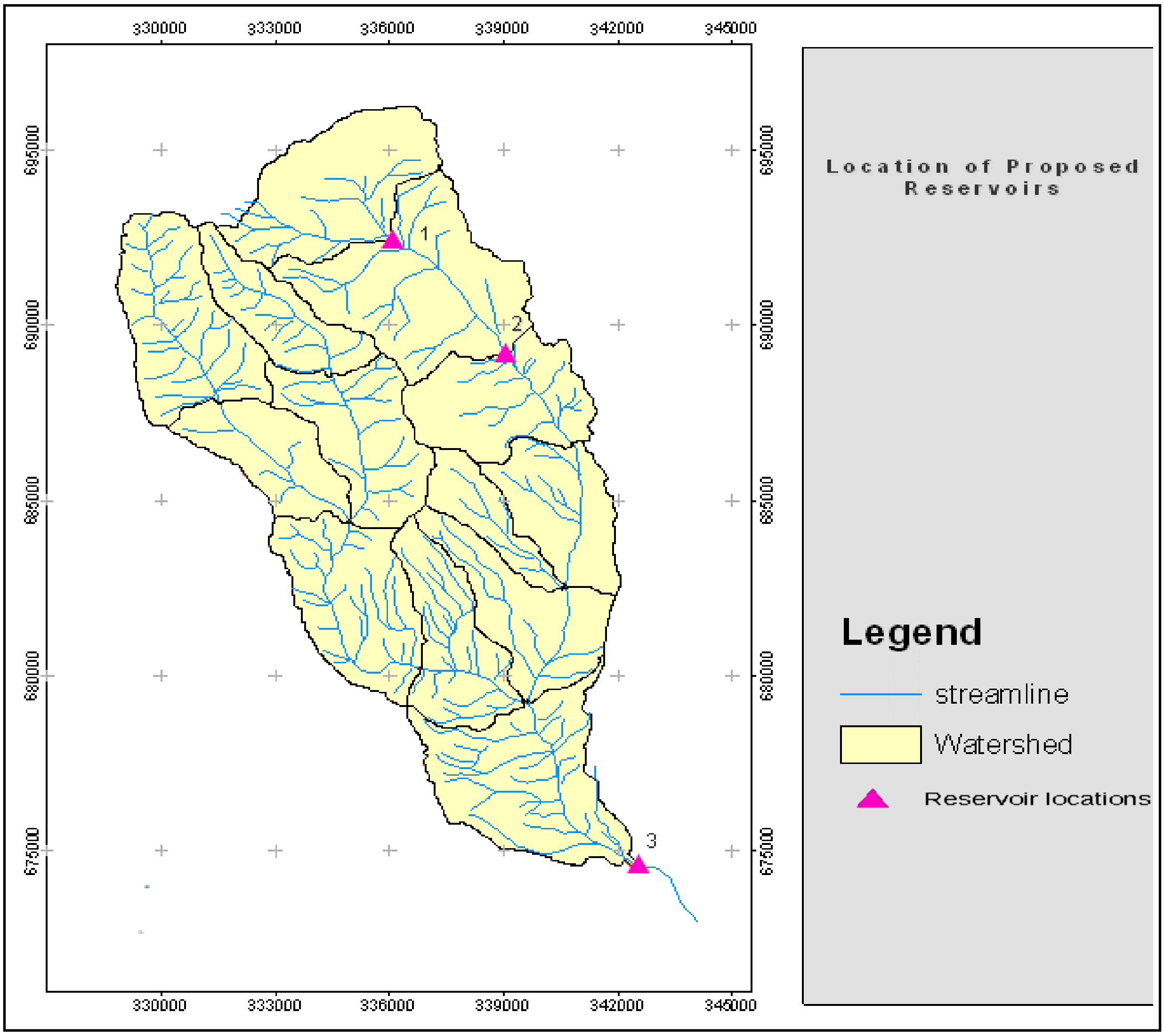


Figure 7.1 Locations of existing (3) and under implementation (1 &2) irrigation projects at Hare watershed

In this research, an attempt was made to include only crops that are more economical beneficial while using the limited available water resources. Table 7.1 provides potential crops selected.

Table 7.1 Potential crops to be irrigated and their respective command area.

Site	Crops	Potential Area (ha)
1	Potato, Onion, Apple	604
2	Potato, Onion, Apple	774
3	Banana, Potato, Cotton	2224

Though there is high rainfall during the wet months, the minimum amount of rainfall during the dry season would be critical for yield and of great importance to the development of adequate deficit irrigation strategies. During this period, soil water content is less than the amount of water required for full growth, which creates a water stress and consecutively low crop yield. In SWAT2005, water applied to a given HRU is obtained from one of five types of water sources: a reach, a reservoir, a shallow aquifer, a deep aquifer, or a source outside the watershed. In addition to the type of water source, the model must know the location of the water source (unless the source is outside the watershed).

7.4.2 Irrigation Water Scheduling

Irrigation water application is commonly scheduled using some measure of reference evaporation and an empirical crop coefficient. The prime objective of irrigation scheduling is to prevent crop water stress throughout the growing stages that avoids the impact of water shortage at some critical stages of plant growth on crop yields. Therefore, the relationship between crop yields and the amount and timing of water received must be established before any optimal irrigation decision can be made. Here, furrow irrigation method is considered at the three sites since it is practiced by famers throughout the watershed for the reason that its low initial capital cost than the other techniques. It should be noted that optimal land was allocated for cash crops such as apple during the simulation process.

In SWAT2005, the user can provide an input of a schedule for irrigating a crop in an HRU, or an automated irrigation triggering approach can be used based on crop water stress or soil moisture depletion. In this research, The CROPWAT model developed by the FAO Land and Water Development Division (FAO, 1992) is implemented to compute the depth and time of irrigation water application for each crop so that the output of the program is used as input for SWAT2005. The program is developed primarily to calculate reference evapotranspiration, crop water requirements and crop irrigation requirements in order to develop irrigation schedules under various management conditions and scheme water supply and to evaluate rain-fed production, drought effects and efficiency of irrigation practices.

When there is a crop stress, an irrigation event is triggered and water is applied depending on the specified depth of application obtained from CROPWAT. Generally, for a given furrow irrigation event, SWAT2005 determines the amount of water available (Irrigation water supply) in the source and compares to irrigation water demanded. If the amount of water available at each reservoir is less than the amount required, SWAT2005 will only apply the available water. If the amount of water specified in an irrigation operation exceeds the amount needed to fill the soil layers up to field capacity water content, the excess water is returned to the source. Irrigation water applied to the HRU is used to fill the soil layers to field capacity beginning with the soil surface layer and working downward until all the water applied is depleted. In this research, an attempt has been made to develop an irrigation scheduling approaches, not necessarily based on full crop water requirement, but that ensure the optimal use of allocated water.

7.4.3 Irrigation Water Allocation Optimization Algorithm

The discussion below describes the step by step procedures followed in writing up components of the irrigation water allocation and use program and the steps in execution the program within the Microsoft Visual Basic environment. Details of the program code, execution and operation procedures are included in Appendix 7.3 of this thesis.

The program is based upon the foundation of user supplied SWAT2005 output files that are simulated scenarios under Chapter 6, other irrigation input data and economic data as well. The first step in the development of the Irrigation water allocation and use program is to compare the yield and gross revenue of agricultural crop fields obtained 'with full irrigation' (WFI) and 'without irrigation' (WOI) scenarios. Normally, the revenue calculated WFI scenario must be surpassed (due to increased yields) than the revenue obtained from the WOI scenario. Crop yields WFI are estimated based on the application of the maximum crop water requirements using CROPWAT at each site with an independent simulation. The next step is to compute a target (optimal) crop yield that can be obtained 'with target irrigation' (WTI) through deficit irrigation to each crop until optimal gross revenue is attained (with minimum crop yield reduction) and an acceptable level of WUE is achieved. In order for irrigation to be beneficial, the additional yield due to deficit irrigation is assumed to increase the revenue to farmers.

The newly developed irrigation water use and allocation decision support tool consists of three steps that must be executed sequentially to operate the program properly, and are briefly described below. The first steps involve the import and modification of required data, while the other two-steps involve model calculations and generate output.

Step 1: Input File Selection:

The program needs four text input files containing all required information that include: the WFI and WOI scenarios output data from the SWAT2005 simulations, additional irrigation input data file and the crop economic data file. During the SWAT2005 simulations, the model calculates actual yields and potential yields and their associated actual evapotranspiration (ET_a) and potential evapotranspiration (ET_m) respectively, and sets them as .hru output file. The ET_a value is associated WOI while the ET_m value is associated WFI scenarios. The new program runs independently of SWAT2005 and it only requires .hru output file that is generated during those simulations, and provides values of key parameters associated with each HRU on daily and monthly bases.

Step 2: Calculations of revenue and irrigation volume application

This section of program allows the user running the model for computing target crop yield, revenue, volume of water used, change in yield, change in revenue, WUE and others relevant parameters at each irrigation project. Moreover, it calculates the optimal depth and volume of irrigation water allocation at each irrigation site.

Step 3: Generate Output Files

At this final stage of the program execution produces two outcomes. First, it generates output files that list the depth and volume of irrigation water used and compares the revenue differences that will be acquired according to the input data provided. Secondly, the program generates an output file that estimates the annual volume of irrigation water demand and volume water saved at the upper sub-watersheds based on the optimal irrigation water allocation and use outlined. The output files generated summarize predicted optimal irrigation water applied at a sub-watershed and watershed scale. The spatial scale of both the hydrological model SWAT that is simulated for each HRU at each sub-watershed and then irrigation water allocation optimization tool for each HRU, sub-watershed and for the whole watershed is given in Appendix 7.4.

Major Computation during optimization

The optimization program computes the most effective way of using the available water resources for irrigation purposes through optimal allocation of the resource given some constraints. Based on the yield–water stress relationships, targeted yields, revenue obtained and WUE for all the crops, the program optimizes the irrigation amounts given to each crop in such a way that crop yield reduction is minimal.

Equations 7.1-7.14 below illustrates derivation that are used to calculate the optimal irrigation depth and volume applied, approximate revenue acquired, and WUE attained. These calculations are undertaken for each of the three furrow irrigation sites and constitute part of the decision support that will aid farmers to appreciate the benefit that they can afford WOI, WTI and WFI scenarios. The program is written based on yield response to water that expresses relative yield reduction ($1-Y_a/Y_m$) as a function of evapotranspiration deficit ($1 - ET_a/ET_m$) for the analysis of the change in percentage of yield to that of change in evapotranspiration. The Ky values for most crops are derived on the assumption that the relationship between relative yield (Y_a/Y_m) and relative evapotranspiration (ET_a/ET_m) is linear and is valid for water deficits of up to about 50 percent or $1 - ET_a/ET_m = 0.5$. The relationships between ($1-Y_a/Y_m$) and ($1-ET_a/ET_m$) are expressed with the following equation (Doorenbos and Kassam, 1979).

$$\left(1-\frac{Y_a}{Y_m}\right)=K_y\left(1-\frac{ET_a}{ET_m}\right) \tag{7.1}$$

Where Y_a and Y_m are actual maximum crop yields (kg), corresponding to ET_a and ETm actual and maximum evapotranspiration (mm), respectively; Ky is the crop yield response factor to water. This relationship is valid for most crops for water deficits in the range $(1 – (ET_a/ET_m) \leq 0.5)$.

For this study, the response of yield to irrigation water supply is quantified through the yield response factor (Ky) which relates relative yield decrease of targeted to that of maximum yield $(1\text{-}Y_t/Y_m)$ to relative targeted to maximum evapotranspiration deficit $(1\text{-}ET_t/ET_m)$. Accordingly, the above linear equation is modified so that it relates the ratio of target evapotranspiration (ET_t) to the ratio of target yield (Y_t). The target evapotranspiration is simply the water volume that must be supplied to the crop in order to achieve the target yield. Therefore, the relationship between Yt, which is greater than Y_a, with Ym can be written as:

$$\left(1-\frac{Y_t}{Y_m}\right)=K_y\left(1-\frac{ET_t}{ET_m}\right) \tag{7.2}$$

In areas where there is a limited amount of available water for irrigation, the problem of optimal water allocation may be considered to be one of maximizing the utilization of the available water supply when conflicts between supply and demand arise. An equity based objective functions can be formulated in order to allocate the limited water among competing crops in a sub-watershed in the context of maintaining equity among competing irrigation sites or sub-watersheds. Consequently, the objective function of the irrigation water allocation and use program would be to minimize crop yield loss between Y_m and Y_t, keeping the revenue obtained from the watershed optimal through saving some volume of irrigation water for downstream users. This function can be mathematically expressed as (Kipkorir, et al., 2001):

$$F = min\sum_{i=1}^{N}\frac{1}{Y_{mi}}(Y_{mi}-Y_{ti})^2 \tag{7.3}$$

However, the function would be difficult to optimize in the above form, and simplification is required. Combing equation 7.2 and 7.3 it can be shown that:

$$\frac{1}{Y_m}(Y_m - Y_t)^2 = Y_m {K_y}^2 \left(1 - \frac{ET_t}{ET_m}\right)^2 \tag{7.4}$$

Thus using equation 7.4 and with an introduction of an economic term P_i, the market price of the crop the objective function is rewritten as:

$$F = min \sum_{i=1}^{N} \frac{P_i Y_{mi} {K_{yi}}^2}{{ET_{mi}}^2} (ET_{mi} - ET_{ti})^2 \tag{7.5}$$

Gross revenue can be computed by multiplying a price Pi with the yield obtained Yi that helps to justify the additional revenue acquired through irrigation water application. Assuming that the ratio ET_t to ET_m without water stress will be the same as the ratio of depths of Target Irrigation (TI) to Full Irrigation (FI); (ET_t/ET_m) = (TI/FI), then it can be shown that:

$$F = min \sum_{i=1}^{N} \frac{P_i Y_{mi} {K_{yi}}^2}{{FI_i}^2} (FI_i - TI_i)^2 \tag{7.6}$$

The objective function is subjected to: (1) the amount of water applied through TI to each crop (HRU) in any sub-watershed should be less than the FI requirement by the crop.

$$TI_i \leq FI_i \tag{7.7}$$

(2) The volume of water required for crop water demand through irrigation is repeated for all triggered crop HRUs in a given day and should be less than the available water supply for each sub-watershed. This is given as:

$$CWD = 10 \sum_{i=1}^{N} \left(\frac{TI_i \cdot A_i}{AE_i}\right) < V_k \tag{7.8}$$

Where CWD is crop water demand for the given day (m^3); *i* is crop HRU number; *n* is number of crop HRUs triggered for the given day; TI*i* is depth of irrigation water (mm); *Ai* is crop HRU area (ha); and *AEi* is application efficiency (%) and V_k quantity of water available at each sub-watershed (m^3).

(3) The revenue obtained through WTI scenario (RVt_i) should be much higher than revenue obtained WOI scenario (RVa_i) and acceptably less than WFI scenario ($\propto RVf_i$).

$$RVa_i < RVt_i < \propto RVf_i \tag{7.9}$$

In the above equations, *Ai* and *AEi* are input data to the model, and *TIi* is the unknown variable for determining the applied irrigation volume and it is estimated by the model depending on the water available at the source. The volume of water associated with the targeted gross revenue is determined through a series of iterations, systematically decreasing 1mm depth of irrigation water applied with FI_i scenario to get TI_i until targeted yield is achieved for each crop based on the above constraints.

As given in equation 7.8, total water demand for a given day at each irrigation site is estimated by summing the crop water demand, seepage, and evaporation losses. Based on the estimation of total water demand for a given day, water for irrigation is released from each reservoir. It should be noted that the extent of crop area irrigated depends on the available water released for irrigation. Hence, in a given irrigation day, the required amount of irrigation water to be released from the reservoir is important. Beside, the annual irrigation water demand for each HRU, sub-watershed and the whole watershed is computed as:

$$V_{HRU}(FI) = \sum_{i=1}^{12} \sum_{j=1}^{n} CWD_i \tag{7.10}$$

$$\boldsymbol{V_{Sub}(FI)} = \sum_{k=1}^{m} (\boldsymbol{V}_{HRU})_k \tag{7.11}$$

$$V_{WAT}(FI) = \sum_{p=1}^{3} \left[\sum_{k=1}^{m} \sum_{i=1}^{12} \left[\sum_{j=1}^{n} CWD_i \right]_j \right]_k \tag{7.12}$$

Where n is the number of days in a month; m is the number of HRU (crops) in a specific sub-watershed at the three sites (p=3).

The equation below is used to compute the revenue (RV_i) acquired for each crop during each iteration.

$$RV_i = P_i Y_m \left(1 - K_y \left(1 - \frac{ET_t}{ET_m}\right)\right) \quad (7.13)$$

In order to determine the relevance of irrigation in the optimization process WUE (Kirda, 2002) were computed. WUE is used in order to quantify the increment in crop yield resulting from the deficit irrigation water application and given as:

$$\boldsymbol{WUE} = 100 \frac{(Y_t - Y_a)}{I_D} \quad (7.14)$$

Where WUE is the irrigation water-use efficiency (kg m^{-3}); I_D is the depth of irrigation (mm); Y_a is the actual grain yield with WOI scenario (kg ha^{-1}); and YI is grain yield obtained with target irrigation (kg ha^{-1}).

The following flow diagram (Figure 7.2) provides a visual reference of the program code used in calculating irrigation depths, crop yield, optimal revenue etc. The first step in the procedure is the calculation of the revenue WOI scenario, referred to above as RV_O. The calculation of RV_O is a boundary condition that assumes the volume of irrigation water applied is zero m^3/ha, and sets the yield equivalent to actual yield and it is WOI scenario obtained directly from the SWAT output file. The procedure then goes through an iterative process that decreases the applied irrigation depth (TI) by 1 mm during each iterations.

Given the new TI*i*, at a specific iteration, the volume of water applied is determined and new target evapotranspiration (*ETti*) and the new target yield (*Yti*) calculated. These values are then used in the calculation of the gross revenue equation (4.21), the output of which is compared to the previous iteration ($RV_{(i-1))}$), in order to determine if the optimal gross benefit value has been obtained. If the gross revenue value of the previous iteration is greater than the current value, the optimal gross revenue and associated variables are set at the previous iteration values.

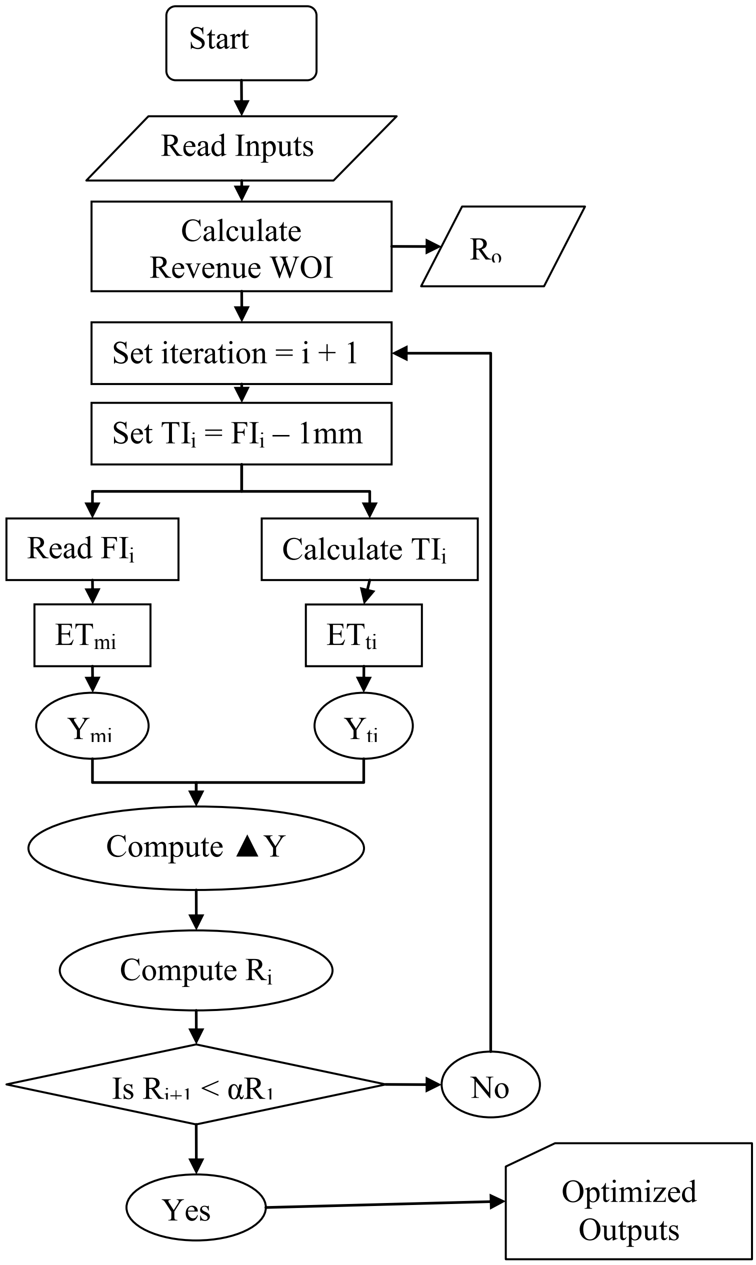


Figure 7.2 Flow diagram of the algorithm

The optimal gross revenue value is then calculated for each HRU and summed over the course of the year and averaged for each year. Through this process the program will determine the optimal economic irrigation volume to supply to plant water requirements taking in to account limited water supply among competing crops in cases where water supply is limited.

7.5 Results and Discussion

7.5.1 Crop Yield Responses 'with' and 'without' Irrigation Scenarios

To evaluate the optimum water allocation strategy among the competing sites, first it was necessary to simulate the SWAT2005 model and analyze its response for WOI and WFI scenarios in terms of output (crop yield), considering the heterogeneous nature of the typical irrigation projects (different crops, soils, temporal and spatial variation of weather parameter etc). Independent simulations were made for each irrigation site so as to use the maximum available water in the stream. CROPWAT was used to compute irrigation water requirements and develop irrigation calendar is for all crops (Appendix 7.5). The program avoids water stress during the flowering stage and maximum relative transpiration. Following strict and carefully formulated irrigation scheduling practices will lead to higher yield returns with lower water waste and inefficiency. In such a context, proper irrigation application remains one of the most effective tools for the conservation and intelligent allocation of limited water resource. The mean seasonal crop yields in Table 7.2 illustrate water stress days and crop yield differences simulated with the WOI and WFI scenarios.

Table 7.2 Mean seasonal crop yields with the WOI and WFI irrigation scenarios.

Sub-watershed	*Crops*	*HRU*	*Irrigation amount (mm)*	*Water stress (days)*		*crop yield (ton/ha)*		
				WOI	**WFI**	**WOI**	**WFI**	**Increase (%)**
2	Apple	12	585.0	73.62	6.54	14.90	19.88	33.4
	Onion	13	245.0	61.36	2.63	9.21	12.31	33.6
	Potato	14	225.0	11.20	0.37	5.26	6.68	27.0
	Apple	52	646.0	60.53	3.60	14.80	21.11	42.6
5	Onion	53	242.0	58.09	8.93	9.16	12.23	33.5
	Potato	52	228.0	11.17	0.15	4.93	5.81	17.8
	Banana	133	656.0	67.86	3.09	8.67	11.67	34.6
	Cotton	134	345.0	42.34	15.00	2.13	2.74	28.6
14	Potato	135	280.0	28.58	5.44	5.10	8.65	69.6

Given in Table 7.2 are the most likely crops that can be produced with irrigation at Hare watershed. It should be noted that simulated results of crop yields should not be regarded as an accurate output, but rather as a useful quantitative approximation of the simulated outputs with respect to specific crops under study. Nevertheless, compared with actual crop yield values at the study area and surrounding, SWAT2005 simulation results were comparable for all crops as reported by the farmers and agricultural office. The yield outputs for each crop vary from year to year but they are roughly in the same range. Therefore, the mean values of the simulations were used for the analysis.

To get a better insight on the simulation outputs, analysis was made mainly for potato. As depicted in the table, the yield of potato with the WOI scenario varies slightly between sub-watersheds 2 & 5 (5.26 ton/ha & 5.2 ton/ha) while both have a significant difference with the downstream sub-watershed 14 (4.04 ton/ha). This difference is attributed to the difference in water stress days of 11.20, 11.17 & 18.58 at sub-watershed 2, 5 & 14 respectively. However, with a decrease in water stress days at all sites, the potato yield obtained at sub-watershed 14 is higher than the other two sites that may be also caused by other factors like soil fertility. Besides, a regression equation between potato yield and soil moisture stress was derived at each month during the crop growing period from the SWAT WOI and WFI scenario simulations to understand the association between the two. The relationship between potato crop yield and water stress days is presented in Figure 7.3 using the WOI scenario.

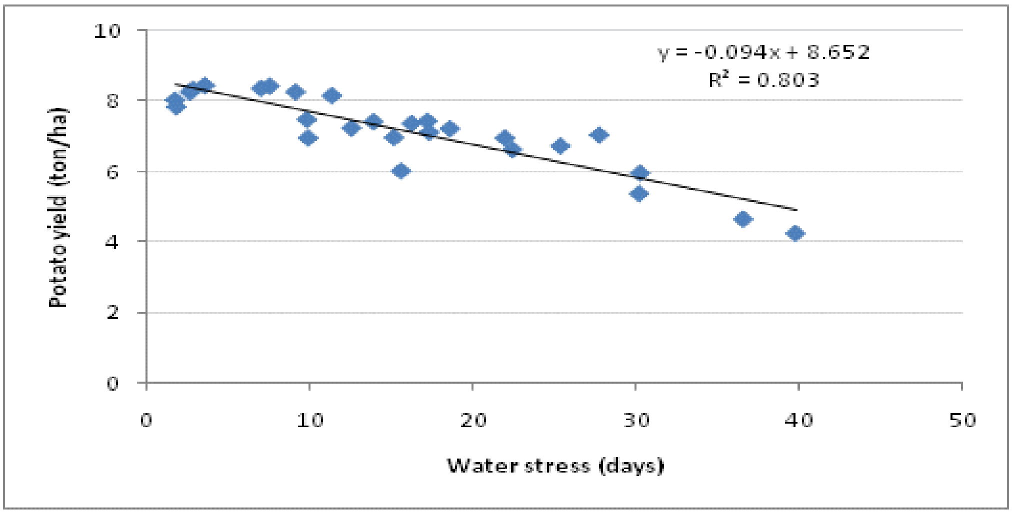


Figure 7.3 Relation between potato yield and water stress days

The linear regression between crop yield and water stress days indicated that about 80 % the variation in potato yield is attributed to water stress days over the predicted 25 years period.

With this simulated values of water stress days (Figure 7.3), the regression plot predicts a decrease of -0.092 ton/ha. As water stress days increases from 2 to 40 days the potato yield is dropped from 8.6 kg/ha to 4.2 kg/ha. The positive value of the intercept indicates that the average potential yield that can be attained without water stress days. On the other hand, the correlation coefficient shows that about 20% of the potato yield variation is not explained by water stress days. Other non-water input factors including fertilizer and land preparation could explain that additional variation. Furthermore, a t-test was carried out on potato crop yield (Appendix 7.6). The results of the t-test indicate that there is statistically significant (at 5% level) difference in the mean yield of potato between WOI and WFI scenarios.

7.5.2 Optimization of Irrigation Water Allocation

An optimization algorithm for allocation of irrigation water among competing demand sites was written in a Microsoft Visual Basic environment. The program is designed in a way to utilize output files from SWAT2005 simulation, and independently prepared economic and irrigation input files. Thus, a simulation-optimization approach is employed for this research. The use of these simulation-optimization procedures offers the advantage to use benefits out of both cases through solving routine based on the output obtained from SWAT2005 simulations. The integration and execution of the hydrologic model with the customized Visual Basic application program that will include specially defined algorithms used for irrigation water allocation optimization, is therefore one of the essential components of this research.

As outlined in Chapter 6, a series of simulations have been conducted using the predefined scenarios that incorporate the crops at each irrigation site. The program estimates monthly irrigation water allotments for each HRU (crop) at each irrigation site (sub-watershed) with the objective of optimal use of available irrigation water based on the minimum crop yields losses within the deficit irrigation principles. Primarily, the program was run for several iterations to examine the effects of different combination of irrigation water application depths, land use change scenarios, and water stress conditions on the crop yields, availability of irrigation water at downstream reach and total returns. To investigate the problems described earlier in this thesis, initially long term simulations for the period of 2010-2035 were performed using SWAT2005 with WOI and WFI scenarios, which are discussed in the previous section. The WFI scenario determines the upper bound of crop production function where the soil moisture does not exceed the field capacity and the WOI scenario was considered as the lower bound function for the optimization process.

After incorporating all the inputs to the newly developed irrigation water allocation and use program, simulation were made to attain optimal depth of irrigation water application at each irrigation site based on the predefined constraints. The target yield attained with this scenario (WTI) represents a value greater than the actual yield with the WOI scenario, but reasonably less than the maximum potential yield with the WFI scenario for each crop considered. The percentage yield loss from the maximum yield was used as one constraint to limit the number of iteration. The results of the analysis using the three scenarios are given in Table 7.3.

Table 7.3 Mean simulation results for the period of 2010-2035 from the three irrigation sites

Sub-WS	Crop	Scenario	Irrigation depth (mm)	ET (mm)	Yield (ton/ha)	Yield reduction (%)	Vol. of saved (m^3/ha)	WUE (kg/m^3)
2	Potato	WFI	225.0	963.0	6.68			2.97
		WTI	204.0	907.0	6.01	10.0	293.33	2.95
		WOI	0.0	851.0	5.20			
	Apple	WFI	585.0	1129.0	19.88			3.40
		WTI	530.0	960.0	18.28	8.1	791.84	3.45
		WOI	0.0	912.0	14.90			
	Onion	WFI	245.0	821.0	12.31			5.02
		WTI	212.0	754.0	10.45	15.1	482.86	4.93
		WOI	0.0	549.0	9.21			
5	Potato	WFI	228.0	914.0	5.81			2.55
		WTI	203.0	820.0	5.00	12.0	358.33	2.46
		WOI	0.0	808.0	4.93			
	Apple	WFI	704.0	1087.0	21.11			3.00
		WTI	646.0	949.0	19.62	7.2	837.36	3.04
		WOI	0.0	850.0	14.80			
	Onion	WFI	242.0	845.0	12.23	10.1		5.05
		WTI	220.0	791.0	11.00		318.37	5.00
		WOI	0.0	570.0	9.16			
14	Potato	WFI	280.0	830.0	8.65			3.09
		WTI	254.0	747.0	7.77	10.0*	366.44	3.06
		WOI	0.0	670.0	5.10			
	Cotton	WFI	345.0	887.0	2.74			0.79
		WTI	301.0	786.0	2.47	10.1*	621.10	0.82
		WOI	0.0	650.0	2.11			
	Banana	WFI	656.0	1118.0	11.67			1.78
		WTI	639.0	1029.0	11.31	5.0*	229.41	1.77
		WOI	0.0	713.0	8.67			

* Maximum yields were simulated by making sub-watersheds 2 and 5 inactive

As indicated in Table 7.3, optimal volume of water saved with an optimal irrigation water application to apple resulting in the optimal yield is greater than optimal volume of water saved with the other crops. This is reflected due to the reason that apple is an annual crop and demands more water and less sensitive to reduced application of irrigation water. The crop yield response plays a critical role in response to irrigation water application in this regard. For instance, potato is associated with a seasonal crop response factor of 1.1, indicating a more rapid decrease in target yield compared to maximum yield for a decrease in target evapotranspiration when compared to that of apple, which is associated with a crop response factor of 0.85. As a result, the percentage of yield reduction for potato is in the range of 10.0 & 12.0%, while for Apple it is 7.2 & 8.0%. Similarly, the percentage of yield loss for onion, cotton and banana were 10.1& 15%, 10.1% and 5.1% respectively.

The total volume of water saved from sub-watershed 2 (1568.03 m^3/ha) and from sub-watershed 5 (1514.06 m^3/ha) were used at the downstream irrigation site. Because of this additional amount of water there is an increase in crop yield and consequently in gross revenue as given in Table 7.4. Therefore, for each crop the most optimal use of water is attained with the specified depths of irrigation with the WTI scenario. Higher application rates will hardly reduce the productivity for upstream situations as this will mainly affect the amount of depleted water that can be used by the downstream users.

In addition, the computed values of WUE are roughly the same for both WTI to WFI scenarios. This means that the yield reduction is not significant to affect WUE and high values were attained with deficit irrigation. Normally, WUE increases when the irrigation amount increases until the maximum application depth attained and begins to decrease with further increases in applied water due to over saturation. Table 7.3 illustrates that WUE of Onion is higher (5.0 kg/m^3) while Cotton provides the lowest WUE (0.82 kg/m^3) than the other crops.

The relationship between WUE and crop yield can be used for determining the optimal irrigation strategy and in this research the relation between the two is observed to be linear that corresponds to the variation to irrigation water application. However, this increase in productivity per unit of supply may lead to lowering of productivity of supply at the watershed level. For example, if more efficient farm practices are used to grow more crops with the same supply for relatively low-valued uses (Cotton), thereby reducing supplies to other farmers that grows higher-valued valued crops like Apple, the overall productivity of watershed supplies may be reduced that also affects the gross revenue acquired from the whole watershed.

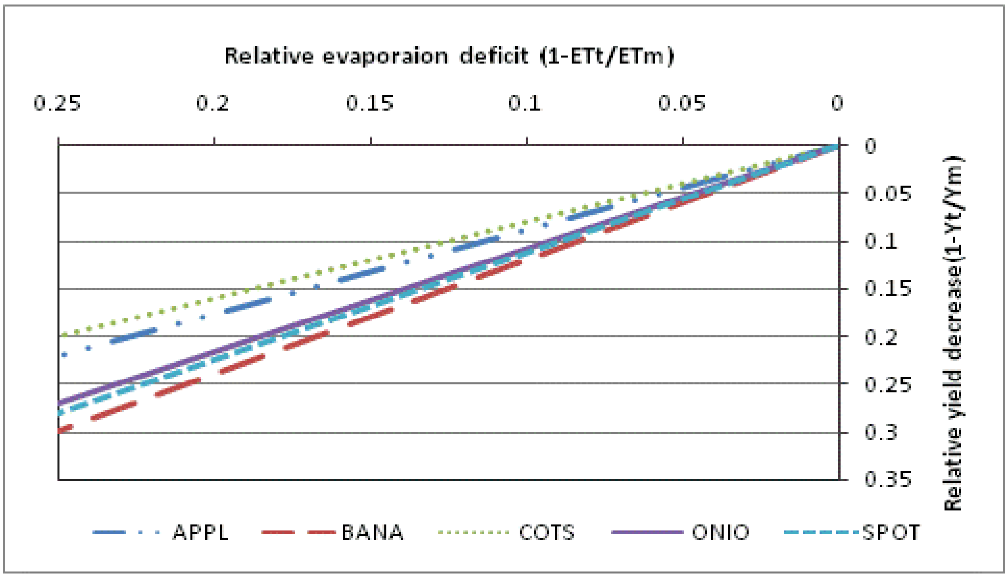


Figure 7.4 Relationship of yield decrease (1-Yt/Ym) and relative ET (1-ETt/ETm).

Figure 7.4 demonstrates the relationship between relative yield decreases (1-Yt/Ym) verses the relative evapotranspiration deficit (1-ETt/ETm) graphically. The correlation of the relative yield decrease and the relative evapotranspiration deficit is determined by the irrigation deficit equation. It can be depicted from the figure that for crop Banana (ky = 1.20), a 25% reduction in the relative evapotranspiration results in a 30% decrease in the maximum yield; whereas an equivalent reduction in the evapotranspiration rate of Apple and cotton with Ky (yield response factor) values of 0.85 and 0.8 results in a 22% and 20% reduction in yield respectively. Similarly, Potato and Onion are equally sensitive to relative reduction in evapotranspiration due to their identical response factor. On the other hand, it can be observed in Table 7.4 that Apple is associated with a higher gross benefit per hectare of land with irrigation due to its higher cash value when compared to other crops.

Therefore, economic benefit with respect to the actual, target and maximum irrigation depth application were calculated that focus on the difference between the revenue lost due to yield decrease as a result of the deficit irrigation schedule at the upper sub-watershed and the additional gross revenue obtained at the downstream irrigation project due to saved water from for upstream water users. Table 7.4 illustrates the actual, target and maximum gross revenue gained for each crop, at each site (sub-watershed) and for the whole watershed.

Table 7.4 Gross revenue gained at HRU, sub-watershed and watershed levels

Sub-watershed	Crops	Revenue WOI* (Birr/ha/yr)	Revenue WTI (Bir/ha/yr)	Revenue WFI (Bir/ha/yr)	Revenue increase WTI (%)	Revenue increase WFI (%)	Revenue dec./increase (%)
		(a)	(b)	(c)	(b)-(a)	(c)-(a)	(c)-(b)
2	Apple	223543	274150	298148	22.64	33.37	-8.05
	Onion	50644	57491	67734	13.52	33.74	-15.12
	Potato	23679	27039	30065	14.19	26.97	-10.06
SW-total		***297866***	***358680***	***395946***	***20.42***	***32.93***	***-9.41***
5	Apple	221862	294323	316726	32.66	42.76	-7.07
	Onion	50404	60494	67298	20.02	33.52	-10.11
	Potato	22166	23976	26136	8.16	17.91	-8.27
SW-total		***294431***	***377793***	***410161***	***28.31***	***39.31***	***-7.89***
14	Banana	26012	33936	28006	30.47	7.67	21.18
	Cotton	12760	14805	13173	16.03	3.24	12.39
	Potato	22925	34970	31110	52.54	35.70	12.41
SW-total		***61697***	***83711***	***72289***	***35.68***	***17.17***	***15.80***
WS-total		**653994**	**833425**	**878396**	**27.44**	**34.31**	**-5.12**

*1€ =12.25 Birr (2007)

As indicated in the above table, all crops were associated with a strong increase in revenue with irrigation water application. As compared to others Apple show the highest increase in gross revenue due to its high price. However, Potato shows the highest increase (52.54%) with the WTI scenario downstream and it seems that irrigation water is the major constraint at the downstream for Potato production. It can also be observed that gross revenue attained downstream with the 'WFI' scenario is less than that of WTI. This is due to the reason that the added amount of water that was saved from the upper two irrigation sites with the optimal application of irrigation water has added values WTI scenario. This is reflected on the gross revenue increase (15.80%) at sub-watershed and reduction at sub-watershed 2 (9.41%) and at sub-watershed 5 (7.89%).

Farmers usually are more concerned with the crop yield that they can acquire through any means. They may consider that supplemental irrigation as a means to maximize the output from their field that makes their land highly productive. They have to participate in any aspects of irrigation water management process. Development agents together with agricultural and irrigation offices has to assist farmers to understand water sharing principles and introduce the concept of equitable utilization of available water resources through deficit irrigation principles.

7.5.3 Utilization of the Optimization Program

As mentioned in previous sections, the developed tool was applied at Hare watershed as case study where there is exist upstream-downstream competing sites for irrigation water use. The developed tool is believed to be an effective tool where there exist irrigation water allocation problems among competing upstream and downstream demand sites. The techniques of simulation and optimization need to be employed in deriving the final outputs. This section describes how the tool can be applied in other similar watersheds.

The SWAT2005 model allows a more detailed and faithful representation of a real-world system's performance than a full optimization model does. However, the optimization approach made it possible to develop prescriptive tool for optimal allocation of irrigation water incorporating the economic impacts. Of course, the application of optimization techniques is most exciting and challenging when it comes to the management of water resources systems due to the large number of decision variables involved, stochastic nature of the inputs, and multiple objectives. In addition, it is no doubt true that unless the demand is more than the supply, and the economic value of a resource is considered both in terms of quality and quantity, optimization is more or less meaningless. Thus, one important example where optimization can play a great role is where there are competing sites for irrigation water use.

While employing the simulation-optimization approach for water resources management, characterization of past, present, and future hydrological conditions in terms of predefined alternative management practices and optimal allocation of the resources are very crucial. Conceptually, the simplest way to integrate the simulation model (SWAT2005) into the optimization tool would be to use the simulation output as input for the optimization model where alternative scenarios are identified through the simulation and optimal allocation of water resources are identified through the optimization process. The use of a combined simulation-optimization approach in this research thus greatly enhanced the utility of the SWAT2005 model by incorporating management goals and constraints into the modeling process through the optimization tool. In this simulation-optimization approach, the desired attributes of the hydrologic and water-resource management systems are specified and the program determines, from a set of several possible strategies, a single management strategy that best meets the desired attributes.

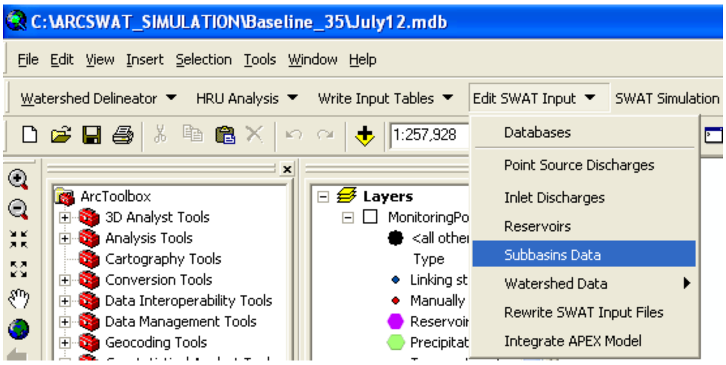
The minimum data and model requirements to utilize the newly developed program are explained as follows. The tool begins with application of outputs from the SWAT2005 model as the baseline conditions. Initially, two independent simulations ('with' and 'without' irrigation scenarios) shall be made with SWAT2005 at each irrigation sites for direct utilization of the tool. Specifically, the *output.hru* file from the simulation output is employed for this purpose. Secondly, an input file that contains economic parameters has to be prepared to evaluate economic benefits from irrigation water use. Thirdly, irrigation efficiency that takes in to account the conveyance and system losses need to included in the tool so that water losses from the diversion to application site are considered. Economic and irrigation data input files are prepared independently in a *text* format. Samples of SWAT2005 simulation output, economic and irrigation input files are included in the CD.

Linking the outputs of SWAT2005, together with the crop economic and irrigation data files, to the optimization tool will yield predictions that are more meaningful in the formulation of a water management policy. The tool can be employed by any interested groups including decision makers and planners so long as they have simulation outputs from SWAT2005, economic and irrigation data inputs and use .net environment that facilitates user interaction with the tool. Overall, the tool requires basic knowledge of hydrological modelling (SWAT) and Visual Basic programming. Besides, it needs some code adjustment if there is a need to use outputs from other models. The step-by-step procedure to utilize the irrigation water allocation program given in the following box 7.1

Box 7.1 Step-by-step procedures for the utilization of irrigation water allocation program

The irrigation water allocation program is developed for Hare watershed as case study. The tool, however, can be used for other watersheds where there is competition for irrigation water between upstream and downstream water users. Here are the step-by-step procedures.

Step 1: *First, run two simulations (with 'full' irrigation and 'without' irrigation scenario) using SWAT2005 (ArcSWAT) model considering all the irrigation sites throughout the watershed. Save 'output.hru' from both simulations as text files.*



Step 2: *Prepare economic input files that contains ID of the crops, crop price, crop yield response factor and crop area as text file. Similarly prepare an irrigation text file that contains; location of the irrigation site (sub-watershed), irrigation efficiency and area irrigated.*

Box 1.1 (continued)

Step 3: *Before running the irrigation water allocation program first open the code of the program in visual basic 2008 and edit the location of the irrigation sites and crop types.*

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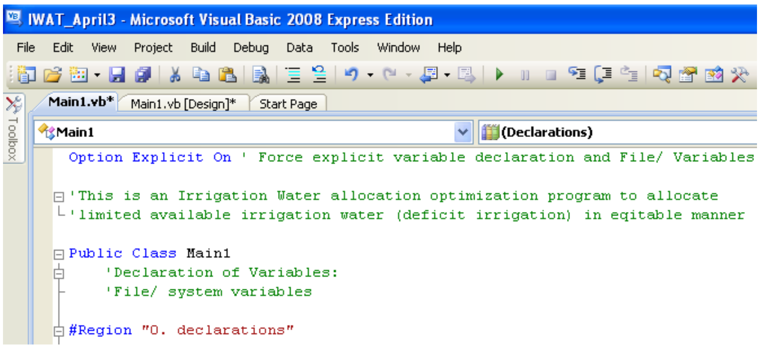
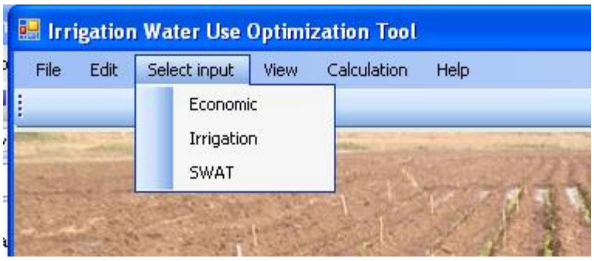
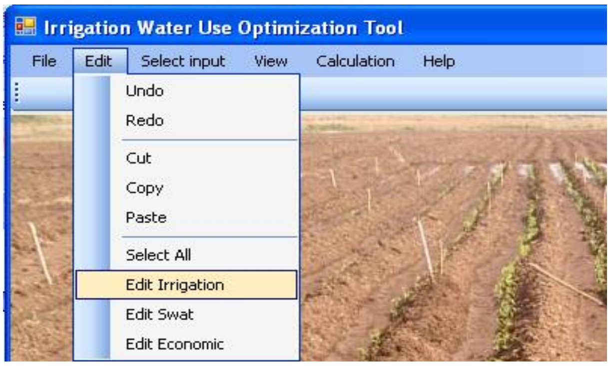


Step 4: *Load the two simulations files (step 1) and economic & irrigation files (step 2)*



Step 5: *If there is a need, edit the input files.*



Step 6: *Run the irrigation water allocation program. By default the output will be in the file folder where the visual basic program is installed. The output files contain the number of iteration, optimal depth and volume of irrigation water applied, targeted ET, crop revenue among other things.*

7.6 Conclusion

The prime objective of this chapter analysis was to develop irrigation water allocation tool for achieving equitable resources utilization while maintaining acceptable economic efficiency. In the face of intense competition among upstream and downstream water users where there is a significant water shortage throughout a watershed, equitable and efficient utilization of water resources has always remained a social goal.

The developed optimal irrigation water allocation program is intended to quantify the problem of irrigation water competition among users at the three sites and propose equitable utilization of the available water resources that will lead to more irrigation water availability at the downstream. Initial simulations were carried out with SWAT2005 to demonstrate irrigation has an important effect in increasing grain yield and identify relation between grain yield to water stress days while simulating WFI and WOI scenarios. Afterward the optimization program was utilized to simulate WTI scenario that entails deficit irrigation principles which gave the better productivity of irrigation water throughout the watershed.

The approach with simulation-optimization procedure offers the advantage to use benefits out of both cases through solving routine based on the output obtained from SWAT2005 simulations. Based on an empirical irrigation water-yield relationship, a nonlinear crop production function is derived and applied in the optimization tool. Because of the simulation model, crop yield is related to the performance of the entire hydrologic system. Consequently, the optimization program relates the volume of irrigation water saved to a tangible economic value in terms of expected gross revenue due to increased yields at the downstream, thereby keeping optimal revenue throughout the watershed. Therefore the simulation-optimization approach connects the hydrologic, agronomic and economic components together into an endogenous system.

The result of the model showed that substantial volume of water, 1568.03 m^3/ha and 1514.06 m^3/ha at sub-watersheds 2 and 5 respectively, can be saved and used by downstream users. This is supported by the non-significant differences between WFI and WTI scenarios for crop yield, and with an equitable water allocation between the upstream and downstream water users for WTI scenario. The economic revenue calculations associated with the WTI scenario is also very insignificant when compared to WFI scenario, which is off-course unlikely to be practical due to limited available water in the watershed.

This introduced optimization approach thus solves the problem of water resources allocation and utilization that has a better advantage when developing alternative management scenarios for the watershed. The tool can aid planners, farmers and policy makers in determining the most effective amount of water to be applied, through the prescription of proper irrigation scheduling procedures that makes the most efficient use of available irrigation water in an equitable manner among the demand sites. Following strict and carefully formulated irrigation scheduling practices and the approach suggested will lead to optimal crops yield return in the watershed. In such a context, proper irrigation water application remains one of the most effective tools for the conservation allocation of limited water resource.

CHAPTER 8

Conclusions and Recommendations

8.1 Conclusions

In recent years, considerable efforts have been put into the development of computer-based models that are powerful tools for investigating the impacts of LUCC on hydrological regimes and optimization of water resources utilization that support integrated water resources management. Within this thesis, an optimization program was developed for optimal utilization of available water resources in an equitable manner among competing upstream-downstream irrigation sites. Before developing the tool, first LUCC during the past four decades was analyzed to identify impacts of these changes on hydrological regime; then two physically based, semi-distributed models, SWAT2005/ArcSWAT and HSPF were tested for their performance at the case study Hare watershed in order to utilize for examining hydrological responses of the watershed to changes in land use and land cover, climate and asses alternative management strategies; finally, based on land use change scenarios projected, the optimization tool was developed.

LUCC experienced in Hare watershed was identified from processed aerial photographs and satellite images. Remote sensing provided useful information on land use and land cover changes since its capability of viewing and repetitive coverage. Step-by-step evaluations of the satellite images and aerial photographs have allowed us to better understand the cause and effect relationship regarding the LUCC over time. Accordingly, spatial databases were developed and analysed using aerial photographs, satellite image and intensive land use mapping using GPS. The results of this analysis can greatly contribute to planning and management of available resources and was utilized as a baseline for further land use and land cover change scenarios development.

On the other hand, systematic data preparation, sensitivity analysis, calibration, validation and uncertainty analysis were performed on the selected models before they are further used for scenario analysis. It should be noted that application of distributed hydrological models for the aforementioned purpose is challenging when used in areas where there is limited data available. This is due to the fact that hydrological models use different spatial, temporal, time series data to predict flow components and hydrologic characteristics over the watershed. Given that both SWAT2005 and HSPF require detailed description of the distribution of physical parameters affecting the water and energy balance at the land surface, the method is facilitated by use of GIS. The use of GIS environment provides a powerful platform for processing of DEM, land use and land cover soil data layers and other topographic attributes and displaying model results in a spatial way, so that it becomes possible to capture local complexities of a watershed. Information generated on sensitivity analysis, calibration, validation, and uncertainty analysis helps to identify and characterize watershed parameters that can assist in developing and achieving watershed management goals.

The specific conclusions drawn from the newly developed optimal irrigation water allocation program, overall LUCC analysis, performances of the SWAT2005 and HSPF simulation models, and hydrological response to LUCC and climate change at Hare Watershed as case study can be summarised as follows:

- An optimization program was developed to optimally allocate available water among competing irrigation sites upstream, middle reach and downstream. The program proposes equitable utilization of the available water resources that will lead to more irrigation water availability at the downstream. Initial simulations were carried out with SWAT2005 to demonstrate irrigation has an important effect in increasing grain yield and identify relation between grain yield to water stress days while simulating 'with full irrigation' and 'without irrigation' scenarios. Afterward the optimization program was utilized to simulate 'with target irrigation' scenario that entails deficit irrigation principles which enable to save substantial volume of water for downstream users and provide better productivity of irrigation water throughout the watershed.

- This introduced optimization approach thus solves the problem of water resources allocation and utilization that has a better advantage when developing alternative management scenarios for a watershed. The optimization program can be used at any watershed as a decision-support tool to assist planners, farmers and policy makers in determining the most effective amount of water to be applied, through the prescription of proper irrigation scheduling procedures that makes the most efficient use of available irrigation water in an equitable manner among the demand sites. In such a context, proper irrigation water application remains one of the most effective tools for the conservation allocation of limited water resource.

- From the LUCC analysis, it can be concluded that Hare watershed had experienced a significant change in land use and land cover over the past four decades. It can be presumed that deforestation and increase in farmland that was manifested by the rapid increase in human population has altered the whole Hare watershed in general and some sub-watershed in particular. The watershed is under high demographical pressure, with a population growth rate estimated at approximately three percent per year and high population density. The extremely low incomes of much of the population result in overexploitation of natural resources in the basin, which seriously affect the sustainable development of the area.

- The modeling purpose and data availability are essential criteria when selecting a hydrological model to evaluate hydrological responses to land use and land cover and management practices to support integrated water resources management plans. For complex water resources management problems where land use and climate change are considered, distributed hydrological models should be used. However, appropriate GIS data and probably advanced data assimilation techniques are needed to improve model application and reduce uncertainty in such applications. The models should only be used in the above mentioned applications if they have been calibrated and validated. Moreover, uncertainty analysis on different sources of uncertainty is essential for a practical application.

- The sensitivity analysis using SWAT2005 has pointed out eight most crucial parameters that control the surface and subsurface hydrological processes of the studied watershed. On the other hand, model calibration and validation have shown both SWAT2005 and HSPF simulated the observed flow quite satisfactorily. The outflow at the watershed outlet has been well reproduced with both models. The models were capable to estimate streamflow composition and contributions from the different land use and land cover classes. However, SWAT2005 was selected for further analysis of impacts of land use and climate change on the hydrological regime and thereafter to perform simulations so that the outputs can be used as inputs for the newly developed optimization tool.

- On the other hand, uncertainty analysis from ParaSol, SUNGLASSES, SUFI-2 and GLUE were discussed. It was identified that ParaSol doesn't consider additional sources of uncertainty that are in general not known and not quantifiable. Unlike the ParaSol that provides only parameter uncertainty analysis, the SUNGLASSES, SUFI-2 and GLUE assess total uncertainty that might be used in comprehensive decision making. The analysis from these methods leads to more selections of parameter combinations and much wider uncertainty ranges. Thus, concern should be given to both the uncertainty associated with model structural error and model parametric uncertainty.

- Following calibration, validation and uncertainty analysis, impacts of past and present LUCC on hydrological regime was carried out. Changes in land use and land cover and their hydrological effects have been regarded as a hotspot and leading issue in scientific research in hydrology. LUCCs recognized to have major impacts on series of hydrological processes, such as runoff, evapotranspiration and groundwater flow. As a result of the LUCC streamflow increased by 12.5% during the wet season and reduced by 30.5% during the dry season between the years 1992-2004. Moreover, the results demonstrate that the upper sub-watershed areas are dominant in surface runoff generation as compared to middle reach and lower part of the watershed. Generally this method of evaluating of the impacts of LUCC on water availability can be used when planning for the agricultural seasons particularly for the time of higher demands of the irrigation water supply. Moreover, it was utilized for generating future land use change scenarios.

- Future impacts of climate and land use and land cover change scenarios were developed and evaluated using possible circumstances of their impacts on irrigation water availability. Accordingly, two climate change and three hypothetical land use change scenarios were considered based on the present land use configuration and possible land use trends in the study area. Results from climate change analysis showed that an increase in future average annual precipitation and average temperature when compared to the baseline period. Consequently, simulation were made that take in to account these scenarios to acquire valuable information on the upstream-downstream linkages with respect to water use interventions in the upland areas and resulting impact at the downstream water users. The results suggest that the small scale irrigation intervention without other conservation and afforestation activities can reduce water availability at the downstream reach of the watershed.

- The limited available irrigation water for upstream-downstream users calls for optimal utilization of available water resources. These ongoing upstream irrigation water abstractions should not be based on the assumption that water is a "free" good and hence needs correct economic approach for assessing development of water projects upstream that considers the livelihoods at downstream users. For this a simulation-optimization approach was employed to develop an irrigation water allocation tool to optimally utilize the available water resources.

- The approach with simulation-optimization procedure offers the advantage to use benefits out of both cases through solving routine based on the output obtained from SWAT2005 simulations. The optimization program attempts to relate the volume of irrigation water saved to a tangible economic value in terms of expected gross revenue due to increased yields at the downstream, thereby keeping optimal revenue throughout the watershed. By doing so, a substantial volume of water was saved at upper sub-watersheds that can be used by downstream users. This is supported by the non-significant differences between 'with full irrigation' and 'with target irrigation' scenarios for crop yield, and with an equitable water allocation between the upstream and downstream water users.

Generally, this study reveals the successful application a newly developed irrigation water allocation tool based on an integrated simulation-optimization approach. The tool can contribute significantly for sustainable development water resources in areas where there is limited available resource. Moreover, the result also highlights that detail understanding of historical land use and cover changes and consequent impacts on streamflow will enhance our capability to predict future impacts of land use and land cover, and climate changes and devise more effective watershed management strategies to sustain the livelihoods of the local community. In short, this study underscores a new effort to bring GIS, RS, hydrologic modelling, and optimization modelling techniques in an integrated fashion in analyzing water management at a watershed context.

8.2 Recommendations

According to the research results, the following major recommendations are made:

- The simulation-optimization approach presented in this thesis can serve as a useful framework for studies in other watersheds. Clearly, certain methodological details may require adjustment on a case-by-case basis. Thus, there has to be further efforts on resources optimization tools based on available land and water and a greater cooperation in model development between decision makers and researchers.

- The cause for LUCC is increased population growth in the study area and the country in general. The current family size of the households in most part of the country will not be sustained by the existing farming practices. Therefore, informal education of households about the impacts of population increase is of paramount importance.

- Data quality and availability should be stressed much more while using distributed hydrological models. The applications SWAT2005 and HSPF models were very challenging and a lack of appropriate data was one of the biggest concerns throughout. Without proper data, model implementation is very difficult if not impossible. The use of new data gathering techniques should be envisaged for developing countries so that local and regional authorities can be involved in integrated and coordinated data compilation.

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Glossary

A Determinist model is a mathematical model in which outcomes are precisely determined through known relationships among states and events, without any room for random variation. In such models, two equal sets of input always yield the same output if run through the model under identical conditions.

Distributed models are models that provide a description of catchment processes at geo-referenced computational grid points within the catchment. They take explicit account of spatial variability of process, input boundary conditions, and/or system (catchment) characteristics

Land cover refers to the physical and biophysical characteristics or state of Earth's surface and immediate, captured in the distribution of vegetation, water, desert, ice and other physical features of the land, including those created solely by human activities e.g., settlements.

Land use refers to the intended use or management of the land cover type by human beings.

Land Use and Land Cover Changes is the shift in intent and/or management constitute land use and land cover.

Hydrologic models are simplified, conceptual representations of a part of the hydrologic cycle. They are primarily used for hydrologic prediction and for understanding hydrologic processes.

Hydrology is defined as the science of water, its properties and states in the atmosphere, on the ground and in the subsurface. It is dealing with the waters interactions with the surrounding media, the water cycle, the distribution above and below the land surface and anthropogenic impacts on these natural systems

Integrated Water Resources Management: is a process which promotes the coordinated development and management of water, land and related resources, in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems.

Model calibration**:** The procedure of adjustment of parameter values of a model to reproduce the response of reality within the range of accuracy specified in the performance criteria.

Model validation: Substantiation that a computerized model within its domain of applicability possesses a satisfactory range of accuracy consistent with the intended application of the model.

Monte Carlo Simulation methods: are a class of computational algorithms that rely on repeated random sampling to compute their results. It generates thousands of probable performance outcomes, called scenarios, which might occur in the future.

***Performance criteria*:** Level of acceptable agreement between model and reality. The performance criteria apply both for model calibration and model validation.

Physically–based model: Model that describes the natural system using the basic mathematical representation of the flow of mass, momentum and various forms of energy.

Potential evapotranspiration: is defined as the rate at which evapotranspiration would occur from a short green crop, completely shading the ground, of uniform height and never short of water

Prediction is a probabilistic statement that something will happen in the future based on what is known today. A prediction generally assumes that future changes in related conditions will not have a significant influence. In this sense, a prediction is most influenced by the "initial conditions" – the current situation from which we predict a change.

Projection specifically allows for significant changes in the set of "boundary conditions" that might influence the prediction, creating "if this, then that" types of statements. Thus, a projection is a probabilistic statement that it is *possible* that something will happen in the future if certain conditions develop.

Scenarios are “plausible and often simplified descriptions of how the future may develop based on a coherent and internally consistent set of assumptions about driving forces and key relationships” (IPCC, 2001).

Scenario analysis is a process of analyzing possible future events by considering alternative possible scenarios. The analysis is designed to allow improved decision-making by allowing consideration of outcomes and their implications.

Semi-distributed models are intermediate approach between lumped and distributed that uses some kind of distribution, either in sub-catchments or in hydrological response units, where areas with the same key characteristics are aggregated to sub-units without considering their actual locations within the catchment.

Sensitivity analysis is the study of how the variation (uncertainty) in the output of a mathematical model can be apportioned, qualitatively or quantitatively, to different sources of variation in the input of a model.

Simulation: A time varying description of a natural system computed by the hydrological model. It can be seen as the model's imitation of the natural system.

Stochastic Model: A mode that has at least one component of random character which is not explicit in the model input, but only implicit or 'hidden'. Therefore, identical inputs will generally result in different outputs if run through the model under, externally seen, identical conditions.

APPENDICES

Appendices to Chapter 4

Appendix 4.1 Soil physical properties required by SWAT2005

NLAYERS	**Number of soil layer**	**Method used**
HYDGRP	Soil hydrologic group (A,B,C,D)	NRCS, 1972 (CN Table)
SOL_ZMX	Maximum rooting depth of soil profile	Estimated from field measurement
SOL_Z	Depth from surface to bottom layer	Field measurement
SOL_BD	Moist bulk density	Core sampler (FAO,1970)
SOL_AWC	Available Water Content of the layer (FC-WP)	Saxton, et al., (1985) method
SOL_K	Saturated hydraulic conductivity	Permiameter methods
TEXTURE	Texture of soil layer	USDA classification
CLAY	Clay content	Hygrometer analysis
SILT	Silt content	Hygrometer analysis
SAND	Sand content	Hygrometer analysis
SOL_CBN	Soil organic carbon content	FAO, (1970) oxidation method
ANION_EXCL	Fraction of porosity anions excluded	- (not used)
SOL_CRK	Crack volume potential of soil	- (not used)
ROCK	Rock fragment content	Field estimation
SOL_ALB	Moist soil albedo	Literature
USLE_K	Soil erodibility factor	- (not used)

Appendix 4.2 Sample soil texture analysis procedure

S.No	**Observations**	**Depth of sampling(cm)**		
		30	60	90
1	Weight of dry soil on oven basis(gm):	100	100	100
2	Hydrometer reading at 4 minutes(gm):	12	13	15
3	Temperature of the suspension for 4 minutes observation	25	26	25
4	Corrected hydrometer reading at 4 minutes(gm):	13	14.20	16
5	Hydrometer reading at 2hours(gm):	4	6	5.50
6	Temperature of the suspension for 2 hours observations	25.5	26	26
7	Corrected hydrometer reading at 2 hours (gm):	5.20	7.20	6.70
8	Amount of silt + clay (gm) :	13	14.20	16
9	Amount of clay (gm):	5.20	7.20	6.70
10	Amount of silt	7.80	7.00	9.30
11	%of silt	7.80	7.00	9.30
12	% of clay	5.20	7.20	6.70
13	% of sand	87	85.8	84

Summary of Test results

S.No.	**Percent of soil fraction**			**Texture of soils**
	Sand	**Silt**	**Clay**	
1	87	7.80	5.20	Loamy Sand
2	85.80	7.00	7.20	Loamy Sand
3	84	9.30	6.70	Sand

Appendix 4.3 Correlation coefficient of soil data

	CLAY	*SILT*	*SAND*	*SOL_K*	*SOL_AWC*	*SOL_BD*	*SOL_OC*	*CEC*
SILT	-0.14							
SAND	-0.80	-0.30						
SOL_K	-0.52	-0.59	0.76					
SOL_AWC	0.55	0.63	-0.81	-0.71				
SOL_BD	0.20	-0.29	0.10	-0.38	-0.70			
SOL_OC	0.41	0.43	0.21	-0.11	0.00	0.07		
CEC	0.29	0.04	0.26	0.26	-0.05	0.15	0.53	
PH	-0.05	0.19	-0.08	-0.11	0.19	0.15	0.18	0.30

Appendices to Chapter 6

Appendix 6.1 storyline that define future climate scenarios

A1. *The A1 storyline and scenario family describe a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. Major underlying themes are convergence among regions, capacity building and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income. The A1 scenario family develops into three groups that describe alternative directions of technological change in the energy system. The three A1 groups are distinguished by their technological emphasis: (1) Fossil intensive (A1FI); (2) Non - fossil energy sources (A1T); and (3) Balance across all sources (A1B)*

A2. *The A2 storyline and scenario family describe a very heterogeneous world. The underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in continuously increasing population. Economic development is primarily regionally oriented and per capita economic growth and technological changes are more fragmented and slower than in other storylines.*

B1. *The B1 storyline and scenario family describe a convergent world with the same global population, that peaks in mid-century and declines thereafter, as in the A1 storyline, but with rapid change in economic structures toward a service and information economy, with reductions in material intensity and the introduction of clean and resource-efficient technologies. The emphasis is on global solutions to economic, social and environmental sustainability, including improved equity..*

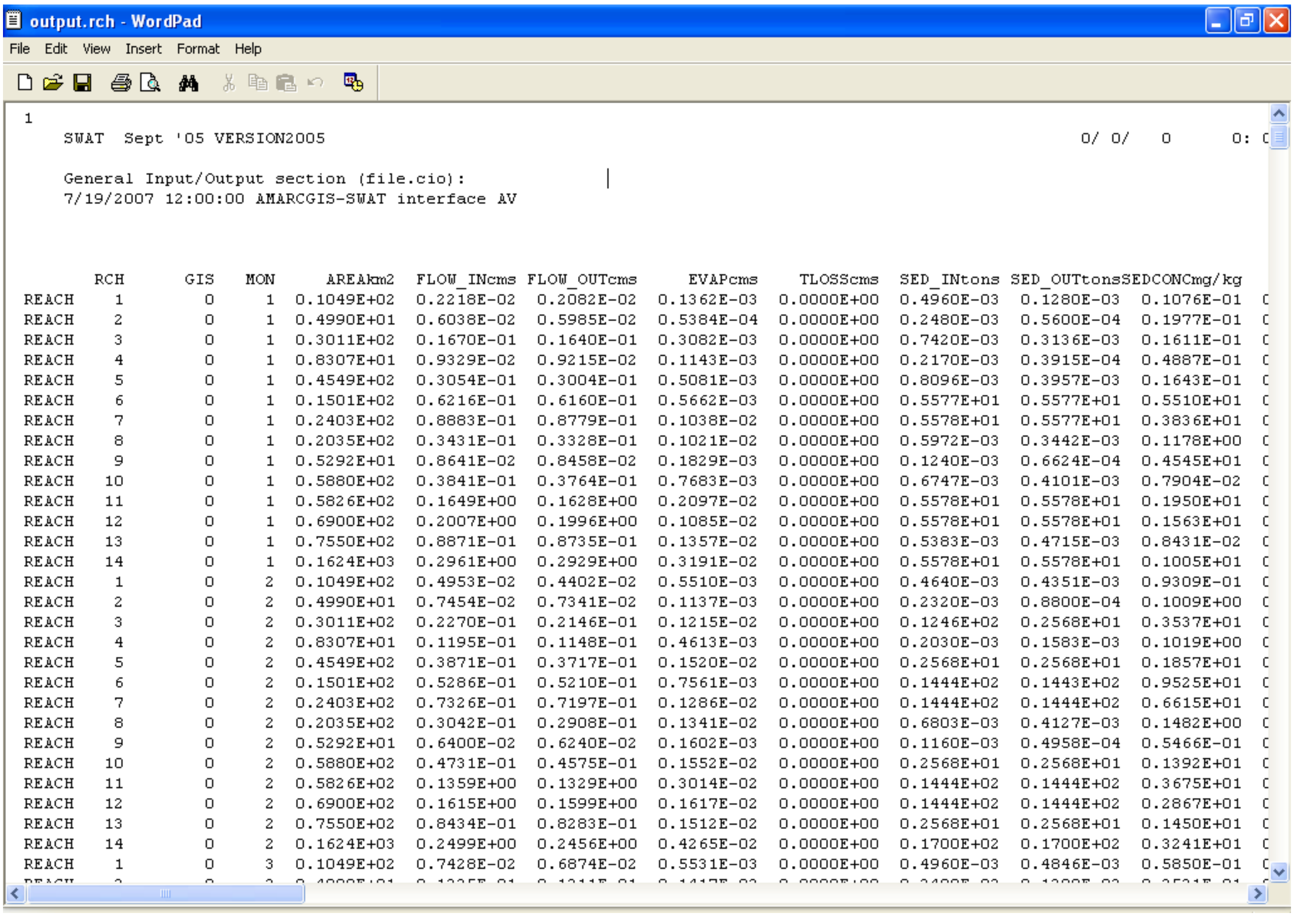
B2. *The B2 storyline and scenario family describe a world in which the emphasis is on local solutions to economic, social and environmental sustainability. It is a world with continuously increasing global population at a rate lower than A2, intermediate levels of economic development, and less rapid and more diverse technological change than in the B1 and A1 storylines. While the scenario is also oriented towards environmental protection and social equity, it focuses on local and regional levels.*

Appendix 6.2 HadCM3 SRES predictor variables downloaded and used in SDSM

No	Predictor variable	Predictor Description	No	Predictor variable	Predictor Description
1	mslpaf	Mean sea level pressure	14	P5zhaf	500hpa divergence
2	P_faf	Surface air flow strength	15	P8_faf	850 hpa* airflow strength
3	P_uaf	Surface zonal velocity	16	P8_uaf	850 hpa zonal velocity
4	P_vaf	Surface meridian velocity	17	P8_vaf	850 hpa meridian velocity
5	P_zaf	Surface vorticity	18	P8_zaf	850 hpa vorticity
6	P_thaf	Surface wind direction	19	P850af	850 hpa geospatial height
7	P_zhaf	Surface divergence	20	P8thaf	850 hpa wind direction
8	P5_faf	500 hpa* airflow strength	21	P8zhaf	850hpa divergence
9	P5_uaf	500 hpa zonal velocity	22	r500af	Relative humidity at 500 hpa
10	P5_vaf	500 hpa meridian velocity	23	r850af	Relative humidity at 500 hpa
11	P5_zaf	500 hpa vorticity	24	rhumaf	Near surface relative humidity
12	P500af	500 hpa geospatial height	25	shumaf	Surface specific humidity
13	P5thaf	500 hpa wind direction	26	tempaf	Mean temperature at 2 m

*hpa is a unit of pressure, 1 hpa=1 mbar=100 pa

Appendix 6.3 Sample reach output from SWAT 2005 simulation



output.rch - WordPad

File Edit View Insert Format Help

```
1
    SWAT  Sept '05 VERSION2005                                    0/ 0/   0      0: C

    General Input/Output section (file.cio):
    7/19/2007 12:00:00 AMARCGIS-SWAT interface AV
```

	RCH	GIS	MON	AREAkm2	FLOW_INcms	FLOW_OUTcms	EVAPcms	TLOSScms	SED_INtons	SED_OUTtons	SEDCONCmg/kg
REACH	1	0	1	0.1049E+02	0.2218E-02	0.2082E-02	0.1362E-03	0.0000E+00	0.4960E-03	0.1280E-03	0.1076E-01
REACH	2	0	1	0.4990E+01	0.6038E-02	0.5985E-02	0.5384E-04	0.0000E+00	0.2480E-03	0.5600E-04	0.1977E-01
REACH	3	0	1	0.3011E+02	0.1670E-01	0.1640E-01	0.3082E-03	0.0000E+00	0.7420E-03	0.3136E-03	0.1611E-01
REACH	4	0	1	0.8307E+01	0.9329E-02	0.9215E-02	0.1143E-03	0.0000E+00	0.2170E-03	0.3915E-04	0.4887E-01
REACH	5	0	1	0.4549E+02	0.3054E-01	0.3004E-01	0.5081E-03	0.0000E+00	0.8096E-03	0.3957E-03	0.1643E-01
REACH	6	0	1	0.1501E+02	0.6216E-01	0.6160E-01	0.5662E-03	0.0000E+00	0.5577E+01	0.5577E+01	0.5510E+01
REACH	7	0	1	0.2403E+02	0.8883E-01	0.8779E-01	0.1038E-02	0.0000E+00	0.5578E+01	0.5577E+01	0.3836E+01
REACH	8	0	1	0.2035E+02	0.3431E-01	0.3328E-01	0.1021E-02	0.0000E+00	0.5972E-03	0.3442E-03	0.1178E+00
REACH	9	0	1	0.5292E+01	0.8641E-02	0.8458E-02	0.1829E-03	0.0000E+00	0.1240E-03	0.6624E-04	0.4545E+01
REACH	10	0	1	0.5880E+02	0.3841E-01	0.3764E-01	0.7683E-03	0.0000E+00	0.6747E-03	0.4101E-03	0.7904E-02
REACH	11	0	1	0.5826E+02	0.1649E+00	0.1628E+00	0.2097E-02	0.0000E+00	0.5578E+01	0.5578E+01	0.1950E+01
REACH	12	0	1	0.6900E+02	0.2007E+00	0.1996E+00	0.1085E-02	0.0000E+00	0.5578E+01	0.5578E+01	0.1563E+01
REACH	13	0	1	0.7550E+02	0.8871E-01	0.8735E-01	0.1357E-02	0.0000E+00	0.5383E-03	0.4715E-03	0.8431E-02
REACH	14	0	1	0.1624E+03	0.2961E+00	0.2929E+00	0.3191E-02	0.0000E+00	0.5578E+01	0.5578E+01	0.1005E+01
REACH	1	0	2	0.1049E+02	0.4953E-02	0.4402E-02	0.5510E-03	0.0000E+00	0.4640E-03	0.4351E-03	0.9309E-01
REACH	2	0	2	0.4990E+01	0.7454E-02	0.7341E-02	0.1137E-03	0.0000E+00	0.2320E-03	0.8800E-04	0.1009E+00
REACH	3	0	2	0.3011E+02	0.2270E-01	0.2146E-01	0.1215E-02	0.0000E+00	0.1246E+02	0.2568E+01	0.3537E+01
REACH	4	0	2	0.8307E+01	0.1195E-01	0.1148E-01	0.4613E-03	0.0000E+00	0.2030E-03	0.1583E-03	0.1019E+00
REACH	5	0	2	0.4549E+02	0.3871E-01	0.3717E-01	0.1520E-02	0.0000E+00	0.2568E+01	0.2568E+01	0.1857E+01
REACH	6	0	2	0.1501E+02	0.5286E-01	0.5210E-01	0.7561E-03	0.0000E+00	0.1444E+02	0.1443E+02	0.9525E+01
REACH	7	0	2	0.2403E+02	0.7326E-01	0.7197E-01	0.1286E-02	0.0000E+00	0.1444E+02	0.1444E+02	0.6615E+01
REACH	8	0	2	0.2035E+02	0.3042E-01	0.2908E-01	0.1341E-02	0.0000E+00	0.6803E-03	0.4127E-03	0.1482E+00
REACH	9	0	2	0.5292E+01	0.6400E-02	0.6240E-02	0.1602E-03	0.0000E+00	0.1160E-03	0.4958E-04	0.5466E-01
REACH	10	0	2	0.5880E+02	0.4731E-01	0.4575E-01	0.1552E-02	0.0000E+00	0.2568E+01	0.2568E+01	0.1392E+01
REACH	11	0	2	0.5826E+02	0.1359E+00	0.1329E+00	0.3014E-02	0.0000E+00	0.1444E+02	0.1444E+02	0.3675E+01
REACH	12	0	2	0.6900E+02	0.1615E+00	0.1599E+00	0.1617E-02	0.0000E+00	0.1444E+02	0.1444E+02	0.2867E+01
REACH	13	0	2	0.7550E+02	0.8434E-01	0.8283E-01	0.1512E-02	0.0000E+00	0.2568E+01	0.2568E+01	0.1450E+01
REACH	14	0	2	0.1624E+03	0.2499E+00	0.2456E+00	0.4265E-02	0.0000E+00	0.1700E+02	0.1700E+02	0.3241E+01
REACH	1	0	3	0.1049E+02	0.7428E-02	0.6874E-02	0.5531E-03	0.0000E+00	0.4960E-03	0.4846E-03	0.5850E-01

Appendices to Chapter 7

Appendix 7.1 Equations used in the design of reservoirs

SWAT2005 considers reservoirs as one of the four types of water bodies (the others being ponds, wetlands, depressions/potholes). Reservoirs are located on the main channel network and they receive water from all sub-watersheds upstream of the water body.

The water balance for a reservoir in SWAT2005 can be mathematically expressed as:

$$V = V_s + V_{fin} - V_{fout} + V_p - V_{ev} - V_{se}$$

Where V is the volume of water in the impoundment at the end of the day (m^3), V_s is the volume of water stored in the water body at the beginning of the day (m^3), V_{fin} *and* V_{fout} are the volume of water entering and flowing out the water body during the day (m^3) respectively, V_p is the volume of rainfall falling on the water body during the day (m^3), V_{ev} is the volume of water removed from the water body by evaporation during the day (m^3), and V_{se} is the volume of water lost from the water body by seepage (m^3).

The V_p, V_{ev} and V_{se} during a given day are computed with equations 4.6, 4.7 and 4.8 respectively.

$$V_p = 10 \cdot P_d \cdot SA$$

$$V_{ev} = 10 \cdot \eta \cdot E_o \cdot SA$$

$$V_{se} = 240 \cdot K_{sat} \cdot SA$$

Where P_d is the amount of rainfall falling on a given day (mm), SA is the surface area of the water body (ha), η is an evaporation coefficient (0.6), E_o is the potential evapotranspiration and K_{sat} is the effective saturated hydraulic conductivity of the reservoir bottom (mm/hr),

The volume of outflow may be calculated using one of four different methods: measured daily outflow, measured monthly outflow, average annual release rate for uncontrolled reservoir, controlled outflow with target release. Among these options available in SWAT2005, the target release approach is selected. This approach tries to mimic general release rules that may be used by reservoir operators. In this approach, the principal spillway volume corresponds to maximum flood control reservation while the emergency spillway volume corresponds to no flood control reservation. In the non-flood season, no flood control reservation is required, and the target storage is set at the emergency spillway volume. During the flood season, the flood control reservation is a function of soil water content.

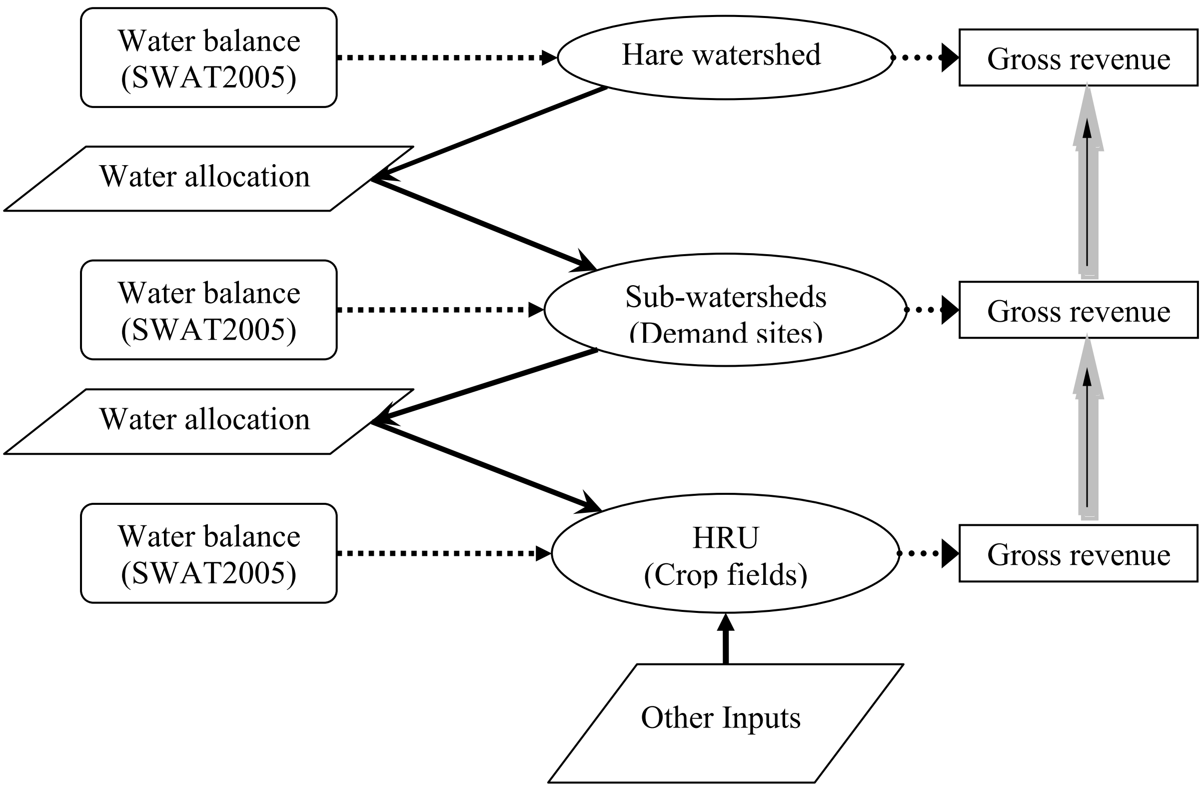
The reservoir surface areas at each site vary with change in the volume of water stored in the reservoir and is updated on daily bases. Any runoff in excess of the amount needed to fill the reservoir during the irrigation water application interval considered to be spilled from the reservoir and not available for storage. However, it was assumed that not all runoff from the sub-watersheds would be available for capture at any individual irrigation sites. In this particular study, 10% of the total runoff would be available to maintain the ecology of the stream network even without the implementation of optimal water allocation procedures and additional 5 % for of the streamflow would be available to downstream irrigation water users to minimize the impacts of the implementation of the two irrigation schemes on the downstream irrigation project.

The stored water at the reservoirs is delivered to the irrigation field based on the daily water requirement of the crops that depend on various factors including location, plant type, soil conditions, and weather conditions. This needs an efficient irrigation scheduling at each irrigation site. Practically in Ethiopia, lack of knowledge about irrigation water management among farmers makes these activities to be the primary responsibility of the agricultural and irrigation offices.

Appendix 7.2 Yield response factor (Ky)

Crop	Vegetative period (1)			Flowering period	Yield formation	Ripening	Total growing period
	Early (1a)	late (1b)	total	(2)	(3)	(4)	
Alfalfa			0.7-1.1				0.7-1.1
Banana							1.2-1.35
Bean			0.2	1.1	0.75.	0.2	1.15
Cabbage	0.2				0.45	0.6	0.95
Citrus							0.8-1.1
Cotton			0.2	0.5		0.25	0.85
Grape							0.85
Groundnut			0.2	0.8	0.6	0.2	0.7
Maize			0.4	1.5*	0.5	0.2	1.25*
Onion			0.45		0.8	0.3	1.1
Pea	0.2			0.9	0.7	0.2	1.15
Pepper							1.1
Potato	0.45	0.8			0.7	0.2	1.1
Safflower		0.3		0.55	0.6		0.8
Sorghum			0.2	0.55	0.45	0.2	0.9
Soybean			0.2	0.8	1.0		0.85
Sugarbeet beet sugar							 0.6-1.0 0.7-1.1
Sugarcane			0.75		0.5	0.1	1.2
Sunflower	0.25	0.5	)	1.0	0.8		0.95
Tobacco	0.2	1.0			0.5		0.9
Tomato			0.4	1.1	0.8	0.4	1.05
Water melon	0.45	0.7		0.8	0.8	0.3	1.1
Wheat winter spring			 0.2 0.2	 0.6 0.65	 0.5 0.55		 1.0 1.15

Appendix 7.4 Spatial scale of the Irrigation water allocation and use tool



Appendix 7.3 Algorism for optimal allocation and use of irrigation water

```
Option Explicit On ' Force explicit variable declaration and File/
Variables
```

'This is an Irrigation Water allocation and Use Optimization program to allocate limited available irrigation water using deficit irrigation pronciples in eqitable manner at Hare watershed

```
Public Class Main1
    'Declaration of Variables

#Region "0. Declarations"

    Public sSwatFileName As String
    Public sSwatFileName100Irr As String
    Public sTempSwatDataFile As String
    Public sTempSwatDataFile100Irr As String
    Public sEconInternalFileName As String
    Public sIrrInternalFileName As String
    Public iMsgVariable As Integer
    Public sCalculateIrrSub As String 'variable used in Revenue Calculations at sub-
watershed level if applicable AGRI-SWAT data Array
    Public sTotAreaAGRIWat As Single 'represents the total area of potentially
irrigable land in the watershed [km]
    Public sAvgAreaHRU As Single 'represents the average area of all AGRI HRU within
the simulations [km]
    Public iHruHigh As Integer 'highest Hru number in Swat data array
    Public iSubHigh As Integer 'highest Sub number in Swat data array
    Public iHruCount As Integer 'total number of HRU's of in the watershed.
    Public iMoCount As Integer 'the total number of months being modeled (it counts
the average for the year data as one month)

    'The following Array variables are contained within the SWAT .out Output file
    Public iSwatArraySize As Long 'ArraySize or number of records of AGRI
    Private lAGRICtr() As Long '[]
    Public sLulc(4) As String  '[]
    Private iHru() As Integer '[]
    Private iGis() As Integer '[]
    Private iSub() As Integer '[]
    Private iMgt() As Integer '[]
    Private iMon() As Integer '[]
    Private sArea() As Single '[km^2] 'Declare all the rest variables as single
    Private iETDif() As Integer '[mm of ]
    Private sTimeStepYld() As Single 'converts the actual Year to date yield to the
yield for the specific time step.
    Private sTimeStepCalcPotentialYld() As Single 'potential yield calculated each
HRU
    Private sTimeStepCalcActYld() As Single 'the actual yield without irrigation

    'the following variables are taken from the SWAT .sbs simulation with
irrigation.
    Private sAEtMax() As Single
    Private iETDiffMax() As Single
    Private sIrrMax() As Single
    Private sYldMax() As Single
    Private sTimeStepYldMax() As Single
    Private sSwatIrrEff() As Single
    Private sTimeStepPotentialYld() As Single

    'The following Variables are Calculated during the Net Revenue
    'Iterations corresponding to each AGRI SWAT record stored in the
    'Array variables above and for each irrigation.
    Private sAppliedIrrSub() As String
```

```
    Private sOptIrrDepth() As Single
    Private sOptIrrVol() As Single
    Private sMaxRevenueWI() As Single
    Private sMaxRevenueWOI() As Single
    Private sMaxRevenueDif() As Single
    Private sOptActIrrYld() As Single
    Private sOptActIrrET() As Single
    Private sOptYldNew() As Single

    'The following are needed in the Net Revenue Calculations:
    'The final value of each is assigned to these variables.
    Private sTargetET() As Single
    Private sIrrDepth() As Single
    Private sIrrVol() As Single
    'Private sRevenue() As Single
    Private sRevenueWOI() As Single
    Private sRevenueTarget() As Single
    Private sYldDivisor() As Single 'values written to file to varify calculations
    Private sTargetYld() As Single 'maximum target yield less than potential yld.
    Private sRevenue1() As Single
    Private sRatioTetPet() As Single
    Private sRatioTetMet() As Single

    'The following Variables are Included in summary tables for each Hru.
    Public iNumHru As Integer 'the number of AGRI HRU's in the SWAT data array
    Private iHruHruSum() As Integer
    Private uSum() As Integer
    Private iSubHruSum() As Integer
    Private sAvgIrrDHruMo() As Single
    Private sAvgIrrDHruYr() As Single
    Private sAvgIrrVHruMo() As Single
    Private sAvgIrrVHruYr() As Single
    Private sAvgIrrRVWIHruMo() As Single
    Private sAvgIrrRVWIHruYr() As Single
    Private sAvgIrrRVWOIHruMo() As Single
    Private sAvgIrrRVWOIHruYr() As Single
    Private sAvgIrrRVDifHruYr() As Single 'The difference between the RV with and
without irrigation
    Private sAvgIrrRecHruYr() As Boolean 'set as true if the irrigation brings
additional RV for the year

    'The following Variables are used solely for the purpose of
    'determining which irrigation to use.
    Private sSub2RVWOIYr() As Single
    Private sSub2RVWIYr() As Single
    Private sSub2RVDifYr() As Single
    Private sSub5RVWOIYr() As Single
    Private sSub5RVWIYr() As Single
    Private sSub5RVDifYr() As Single
    Private sSub24RVWOIYr() As Single
    Private sSub24RVWIYr() As Single
    Private sSub24RVDifYr() As Single
    Private sRecIrrSub() As String
    Private sTotIrrVolSubYr() As Single
    Private iRecIrrSubInt() As Integer
    Private sSub2IrrVolYr() As Single
    Private sSub5IrrVolYr() As Single
    Private sSub24IrrVolYr() As Single
    Private sRVMaxDif() As Single

    'The following Variables are Included in summary tables for each Sub-watershed.
    'Public iNumSub As Long 'the number of Subbassins in the data array
    Public iNumSub As Integer 'the number of Subbassins in the data array
    Private iSubSubSum() As Integer
    Private sMoAvgIrrVSubYr() As Integer
    Private sMoAvgIrrDSubYr() As Integer
    Private iMoHruSubSum() As Integer
    Private iHruSubSum() As Integer
```

```
    Private sAvgIrrDSubMo() As Single
    Private sAvgIrrDSubYr() As Single
    Private sAvgIrrVSubMo() As Single
    Private sAvgIrrVSubYr() As Single
    Private sAvgIrrRVWISubMo() As Single
    Private sAvgIrrRVWISubYr() As Single
    Private sAvgIrrRVWOISubMo() As Single
    Private sAvgIrrRVWOISubYr() As Single
    'The following Variables are Included in summary tables for the entire
watershed.
    Private sAvgIrrDWatMo As Single
    Private sAvgIrrDWatYr As Single
    Private sAvgIrrVWatMo As Single
    Private sAvgIrrVWatYr As Single
    Private sAvgIrrRVWIWatMo As Single
    Private sAvgIrrRVWIWatYr As Single
    Private sAvgIrrRVWOIWatMo As Single
    Private sAvgIrrRVWOIWatYr As Single
    'Variables that are Included in the monthly summary tables for each Subbasin.
    Public iMoNumSub As Integer 'holds the size of this array group
    Private iMoSubSubSum() As Integer
    Private iMoMonSubSum() As Integer
    Private sMoAvgIrrDSubMo() As Single
    Private sMoAvgIrrVSubMo() As Single
    Private sMoAvgRVWISubMo() As Single
    Private sMoAvgRVWOISubMo() As Single

    'Variables that are Included in monthly summary tables for the entire watershed.
    Private iMoMonWatMo(11) As Integer
    Private sMoAvgIrrDWatMo(11) As Single
    Private sMoAvgIrrVWatMo(11) As Single
    Private sMoAvgRVWIWatMo(11) As Single
    Private sMoAvgRVWOIWatMo(11) As Single

    'list of Economic Variables Needed for the execution of the program
    Public iEconArraySize As Integer
    Private sEconIdCrop(4) As String
    Private sEconDescription(4) As String
    Private sEconKy(4) As Single
    Private sEconPCrop(4) As Single
    Private sAreaShare(4) As Single

    'list of irrigation Variables Needed for the execution of the program
    Public iIrrigArraySize As Integer
    Private sIrrSub(2) As String 'Abbreviation code for
    Private sIrrEff(2) As Single 'Irrigation efficiency []
    Private sIrrSubArea(2) As Single 'Average farm area [ha]

    End Sub
#End Region

#Region "1. Selecting and Loading"

    'STEP 1: Primary call procedures
    'Code Required for Selecting and Loading Input File Data.
    'Selects ECONOMIC input data file
    Private Sub EconSelect_Click(ByVal sender As System.Object, ByVal e As
System.EventArgs) Handles EconSelectToolStripMenuItem.Click, SelectFileMenu.Click
        Dim sEconOutputFile As String = My.Application.Info.DirectoryPath &
"\TempEconData.txt"
        Dim sTitlePhrase As String = "Select Economic Input Data File."
        Dim sSelectFile As String = SelectFile(sTitlePhrase)
        sEconInternalFileName = My.Application.Info.DirectoryPath &
"\TempEconData.txt"
        Call CreateInternalFile(sSelectFile, sEconOutputFile)
        MsgBox("Economic Variables Have Been Loaded", vbOKOnly, "Program Status
Message")
    End Sub
```

```
    'STEP 1: Primary call procedures
    'Selects IRRIGATION input data file
    Private Sub IrrSelect_Click(ByVal sender As System.Object, ByVal e As
System.EventArgs) Handles IrrSelectToolStripMenuItem.Click, SelectFileMenu.Click
        Dim sIrrOutputFile As String = My.Application.Info.DirectoryPath &
"\TempIrrigData.txt"
        Dim sTitlePhrase As String = "Select Irrigation Input Data File."
        Dim sSelectFile As String = SelectFile(sTitlePhrase)
        sIrrInternalFileName = My.Application.Info.DirectoryPath &
"\TempIrrigData.txt"
        Call CreateInternalFile(sSelectFile, sIrrOutputFile)
        MsgBox("Irrigation Variables Have Been Loaded", vbOKOnly, "Program Status
Message")
    End Sub
    'STEP 1: Primary call procedures'Selects SWAT input data file
    Public Sub SwatSelect_Click(ByVal sender As System.Object, ByVal e As
System.EventArgs) Handles SwatSelectToolStripMenuItem.Click, SelectFileMenu.Click
        'Dim iMsgVariable As Integer
        Dim sSelectFile As String
        Dim sSelectFileMax As String
        Dim sTitlePhrase As String
        sTitlePhrase = "Select First SWAT (1) without irrigation Input File."
        sSelectFile = SelectFile(sTitlePhrase)
        sTitlePhrase = "Select Second SWAT (2) with irrigation Input File."
        sSelectFileMax = SelectFile(sTitlePhrase)
        sTempSwatDataFile = My.Application.Info.DirectoryPath &
"\TempSwatDataFile.txt"
        sTempSwatDataFile100Irr = My.Application.Info.DirectoryPath &
"\TempSwatDataFile100Irr.txt"
        sSwatFileName = sTempSwatDataFile
        sSwatFileName100Irr = sTempSwatDataFile100Irr
        Call FormatSwatFile(sSelectFile)
        Call FormatSwatFileMax(sSelectFileMax)
        MsgBox("SWAT Variables Have Been Loaded", vbOKOnly, "Program Status
Message")
    End Sub
    'Step 1: 2nd level Support Procedures
    'The following function 'Triggers the Open File Dialog Box.
    Public Function SelectFile(ByVal sTitlePhrase As String) As String
       OpenFileDialog1.Title = sTitlePhrase
        OpenFileDialog1.ShowDialog()
        SelectFile = OpenFileDialog1.FileName
    End Function
    'Step 1: 2nd level Support Procedures
    'procedure that copies the selected file to a temp internal data file
    Public Sub CreateInternalFile(ByVal sSelectFile As String, ByVal
sInternalFileName As String)
        Dim lctr As Long
        Dim i As Long
        Dim lFileLength As Integer
        Dim sFileLines() As String
        lFileLength = DataFileLength(sSelectFile)
        lctr = 0
        FileOpen(1, sSelectFile, OpenMode.Input)
        ReDim sFileLines(0 To lFileLength)

        'Do loop loads input data into a temporary array.
        Do While Not EOF(1)
            sFileLines(lctr) = LineInput(1)
            lctr += 1
        Loop
        FileClose(1)
        lctr = lctr - 1
        'For loop writes temp file
        FileOpen(1, sInternalFileName, OpenMode.Output)
        For i = 0 To lctr
            Call PrintDataFile(sFileLines(i))
        Next i
```

```
        FileClose(1)
    End Sub
    'Step 1: 2nd level Support Procedures
    'This function reformats the data if the .sbs file was exported from SWAT2005.
    Public Sub FormatSwatFile(ByVal sSelectFile As String)
        Dim sFileLines() As String
        Dim sTempLineInput As String
        Dim lctr As Long
        Dim i As Long
        Dim lFileLength As Long
        Dim iHeaderLines As Integer  'counts the number of lines in the header
        lFileLength = DataFileLength(sSelectFile)
        lctr = 0
        iHeaderLines = 0
        FileOpen(1, sSelectFile, OpenMode.Input)

        'Do While (Microsoft.VisualBasic.Left(sTempLineInput, 4) <> "LULC")
        Do While Not EOF(1)
            sTempLineInput = LineInput(1)
            iHeaderLines += 1
        Loop
        FileClose(1)
        lctr = lctr - 1

       'The following codes creates a temp file of SWAT data.
        FileOpen(1, sTempSwatDataFile, OpenMode.Output)
        PrintLine(1, "LULC,HRU, GIS, SUB, MGT, MON, AREAkm2, PRECIPmm, SNOFALLmm,
SNOMELTmm, IRRmm, PETmm, ETmm, SW_INITmm, SW_ENDmm, PERCmm, GW_RCHGmm, DA_RCHGmm,
REVAPmm, SA_IRRmm, DA_IRRmm, SA_STmm, DA_STmm, SURQ_GENmm, SURQ_CNTmm, TLOSSmm,
LATQmm, GW_Qmm, WYLDmm, DAILYCN, TMP_AVdgC, TMP_MXdgC, TMP_MNdgCS, OL_TMPdgCS,
OLARMJ/m2, SYLDt/ha, USLEt/ha, N_APPkg/ha, P_APPkg/ha, NAUTOkg/haPA, UTOkg/ha,
NGRZkg/ha, PGRZkg/haNC, FRTkg/haPC, FRTkg/haNR, AINkg/ha, NFIXkg/ha, F-MNkg/ha, A-
MNkg/ha, A-SNkg/ha, F-MPkg/haAO, NameNum, L-APkg/ha, A-SPkg/ha, DNITkg/ha, NUPkg/ha,
PUPkg/ha, ORGNkg/ha, ORGPkg/ha, SEDPkg/haNS, URQkg/haNL, ATQkg/ha, NO3Lkg/haNO,
3GWkg/ha, SOLPkg/ha, P_GWkg/ha, W_STRS, TMP_STRS, N_STRS, P_STRS, BIOMt/ha, LAI,
YLDt/ha, BACTPct, BACTLPct")

        'The following if statement test for the two .sbs file types.
        If Mid(sFileLines(0), 5, 1) = Chr(9) Then
            'The data file is exported from SWAT2005 and is tab delineated.
            For i = 0 To lctr
                Call FindReplace(sFileLines(i), Chr(9), ",", lctr)
                Call PrintDataFile(sFileLines(i))
            Next i
        Else
            For i = 0 To lctr
                Call FormatBasinSwatLine(sFileLines(i))
            Next i
        End If
        FileClose(1)
        sSwatFileName = sTempSwatDataFile
    End Sub
    'Step 1: 2nd level Support Procedures
    Public Sub FormatSwatFileMax(ByVal sSelectFile As String)
        'This function reformats the data if the .sbs file was exported   'from
ArcView
        Dim sFileLines() As String
        Dim sTempLineInput As String
        Dim lctr As Long
        Dim i As Long
        Dim lFileLength As Long
        Dim iHeaderLines As Integer 'counts the number of lines
        lFileLength = DataFileLength(sSelectFile)
        lctr = 0
        iHeaderLines = 0
        FileOpen(1, sSelectFile, OpenMode.Input)

        'Do While (Microsoft.VisualBasic.Left(sTempLineInput, 4) <> "LULC")
```

```
        Do While Not EOF(1)
            sTempLineInput = LineInput(1)
            iHeaderLines += 1
        Loop

        FileClose(1)
        lctr = lctr - 1
        FileOpen(1, sTempSwatDataFile100Irr, OpenMode.Output)
        PrintLine(1, "HRU, GIS, SUB, MGT, MON, AREAkm2, PRECIPmm, SNOFALLmm,
SNOMELTmm, IRRmm, PETmm, ETmm, SW_INITmm, SW_ENDmm, PERCmm, GW_RCHGmm, DA_RCHGmm,
REVAPmm, SA_IRRmm, DA_IRRmm, SA_STmm, DA_STmm, SURQ_GENmm, SURQ_CNTmm, TLOSSmm,
LATQmm, GW_Qmm, WYLDmm, DAILYCN, TMP_AVdgC, TMP_MXdgC, TMP_MNdgCS, OL_TMPdgCS,
OLARMJ/m2, SYLDt/ha, USLEt/ha, N_APPkg/ha,P_APPkg/ha, NAUTOkg/haPA, UTOkg/ha,
NGRZkg/ha, PGRZkg/haNC, FRTkg/haPC, FRTkg/haNR, AINkg/ha, NFIXkg/ha, F-MNkg/ha, A-
MNkg/ha, A-SNkg/ha, F-MPkg/haAO, NameNum, L-APkg/ha, A-SPkg/ha, DNITkg/ha, NUPkg/ha,
PUPkg/ha, ORGNkg/ha, ORGPkg/ha, SEDPkg/haNS, URQkg/haNL, ATQkg/ha, NO3Lkg/haNO,
3GWkg/ha, SOLPkg/ha, P_GWkg/ha, W_STRS, TMP_STRS, N_STRS, P_STRS, BIOMt/ha, LAI,
YLDt/ha, BACTPct, BACTLPct")
        'The following if statement test for the two .sbs file types.

        If Mid(sFileLines(0), 5, 1) = Chr(9) Then
            'IF this is true the data file is exported from ArcView and   'is tab
delineated.
            For i = 0 To lctr
                Call FindReplace(sFileLines(i), Chr(9), ",", lctr)
                Call PrintDataFile(sFileLines(i))
            Next i
        Else
            For i = 0 To lctr
                Call FormatBasinSwatLine(sFileLines(i))
            Next i
        End If
        sSwatFileName100Irr = sTempSwatDataFile100Irr
        FileClose(1)
    End Sub
    'Step 1: 3rd Level Support Procedures
    'Function determines the number of lines within an input file.
    Public Function DataFileLength(ByVal sFileName As String) As Long
        Dim sLineRecord As String
        Dim lctr As Long
        lctr = 0
        FileOpen(1, sFileName, OpenMode.Input) 'open File
        Do While Not (EOF(1))
            sLineRecord = LineInput(1)
            lctr = lctr + 1
        Loop
        FileClose(1)
        lctr = lctr + 1
        DataFileLength = lctr
    End Function
    'Step 1: 3rd Level Support Procedures
    'Function replaces data in a search string
    Public Sub FindReplace(ByRef sSearchString As String, _
    ByVal sFindWhat$, ByVal sReplaceWith$, ByVal lctr As Long)
        Dim i As Long 'counter for loop control
        Dim iPos As Integer, iStart As Integer
        iStart% = 1
        Do
            For i = 0 To lctr
                'Find beginning position
                iPos% = InStr(iStart%, sSearchString, sFindWhat$)
                'If not there, then get out
                If iPos% = 0 Then Exit Do
                'Combine left portion, new string, and right portion
                sSearchString = Microsoft.VisualBasic.Left(sSearchString, iPos% - 1)
& sReplaceWith$ & Microsoft.VisualBasic.Right(sSearchString, Len(sSearchString) -
iPos% - Len(sFindWhat$) + 1)
```

```
                'Calculate where to begin next search
                iStart% = iPos% + Len(sReplaceWith$)
            Next i
        Loop

    End Sub
    'Step 1: 3rd Level Support Procedures
    'Public Sub PrintDataFile(ByVal sFileLines As String)

    Public Sub PrintDataFile(ByVal sSwatFileLine As String)
        PrintLine(1, sSwatFileLine)
    End Sub
#End Region

#Region "2. Runing Calculation"
    'STEP 3: Primary call procedures
    'Code Required for Running Revenue Calcualtions
    Private Sub RevenueSub2_Click(ByVal sender As System.Object, ByVal e As
System.EventArgs) Handles SubWS2ToolStripMenuItem.Click
        Dim iIrrType As Integer 'Selects the type of irrigation
        sCalculateIrrSub = "irr_Sub2"
        iIrrType = 0
        Call InitiateRVCalc(iIrrType)
        Call CompareRVIrrSub()
        Call CalcOptimalIrrVol()
        Close()
    End Sub
    Private Sub RevenueSub2_Click()
        Dim iIrrType As Integer 'Selects the type of irrigation
        'Dim i As Integer
        sCalculateIrrSub = "irr_Sub2"
        iIrrType = 0
        Call InitiateRVCalc(iIrrType)
        Call CompareRVIrrSub()
        Call CalcOptimalIrrVol()
        Close()
    End Sub
    'STEP 3: Primary call procedures
    Private Sub RevenueSub5_Click(ByVal sender As System.Object, ByVal e As
System.EventArgs) Handles SubWS5ToolStripMenuItem.Click
        Dim iIrrType As Integer 'Selects the type of irrigation
        sCalculateIrrSub = "irr_Sub5"
        iIrrType = 1
        Call InitiateRVCalc(iIrrType)
        Call CompareRVIrrSub()
        Call CalcOptimalIrrVol()
        Close()
    End Sub
    'STEP 3: Primary call procedures
    Private Sub RevenueSub14_Click(ByVal sender As System.Object, ByVal e As
System.EventArgs) Handles SubWS14ToolStripMenuItem.Click
        Dim iIrrType As Integer 'Selects the type of irrigation
        sCalculateIrrSub = "irr_Sub14"
        iIrrType = 2
        Call InitiateRVCalc(iIrrType)
        Call CompareRVIrrSub()
        Call CalcOptimalIrrVol()
        Close()
    End Sub
    'STEP 3: Primary call procedures
    Private Sub Revenue_All_Click(ByVal sender As System.Object, ByVal e As
System.EventArgs) Handles AllToolStripMenuItem.Click
        Dim iRVCalc As Integer
        iRVCalc = 10
        Call InitiateRVCalc(iRVCalc)
        Call CompareRVIrrSub()
        Call CalcOptimalIrrVol()
        Close()
```

```
    End Sub
    Private Sub Revenue_All_Click()
        Dim iRVCalc As Integer
        iRVCalc = 10
        Call InitiateRVCalc(iRVCalc)
        Call CompareRVIrrSub()
        Call CalcOptimalIrrVol()
        Close()
    End Sub
    'STEP 3: Primary call procedures
    'Procedure runs all RV calcualtions without user prompting
    Private Sub RunCalc_Click(ByVal sender As System.Object, ByVal e As
System.EventArgs)
        Call Revenue_All_Click()
        Call CompareRVIrrSub()
        Call CalcOptimalIrrVol()
        Close()
    End Sub
    'STEP 3: 2nd Level support procedures
    Public Sub InitiateRVCalc(ByVal iIrrType As Integer)
        Call LoadEconVariables() 'Loads Econ data variables
        Call LoadIrrigVariables() 'Loads Irrig data variables
        Call LoadSwatVariables() 'Loads Swat Variables into variable array
        Call LoadSwatVariablesMax() 'Loads Swat Variables running Swat WFI
        Call CalculateRevenue(iIrrType) 'Calculates and writes to data file.
    End Sub
    'STEP 3: 3rd Level support procedures
    Public Sub LoadEconVariables()
        Dim iCtr As Integer
        Dim sEconIdCropTemp As String
        sEconIdCropTemp = "A111"
        Dim sEconDescriptionTemp As String
        sEconDescriptionTemp = "Bean"
        Dim sEconKyTemp As Single
        Dim sEconPCropTemp As Single
        Dim sEconColHeadings As String
        Dim sAreaShareTemp As Single
        sEconInternalFileName = My.Application.Info.DirectoryPath &
"\TempEconData.txt"
        FileOpen(1, sEconInternalFileName, OpenMode.Input)
        sEconColHeadings = LineInput(1) 'Read line into variable.
        iCtr = 0
        Do While Not (EOF(1))
            Input(1, sEconIdCropTemp)
            Input(1, sEconDescriptionTemp)
            Input(1, sEconKyTemp)
            Input(1, sEconPCropTemp)
            Input(1, sAreaShareTemp)
            sEconIdCrop(iCtr) = sEconIdCropTemp
            sEconDescription(iCtr) = sEconDescriptionTemp
            sEconKy(iCtr) = sEconKyTemp
            sEconPCrop(iCtr) = sEconPCropTemp
            sAreaShare(iCtr) = sAreaShareTemp
            iCtr = iCtr + 1
        Loop
        FileClose(1)
        FileClose(2)
        iEconArraySize = iCtr
    End Sub
    'STEP 3: 3rd Level support procedures
    Public Sub LoadIrrigVariables()
        Dim iCtr As Integer
        Dim sIrrSubTemp As String
        sIrrSubTemp = "IrrSub long"
        Dim sIrrEffTemp As Single
        Dim sIrrSubAreaTemp As Single
        Dim sIrrColHeadings As String
```

```
        sIrrInternalFileName = My.Application.Info.DirectoryPath &
"\TempIrrigData.txt"
        FileOpen(1, sIrrInternalFileName, OpenMode.Input)
        sIrrColHeadings = LineInput(1)
        iCtr = 0

        Do While Not (EOF(1))
            Input(1, sIrrSubTemp)
            Input(1, sIrrEffTemp)
            Input(1, sIrrSubAreaTemp)
            sIrrSub(iCtr) = sIrrSubTemp
            sIrrEff(iCtr) = sIrrEffTemp
            sIrrSubArea(iCtr) = sIrrSubAreaTemp
            iCtr = iCtr + 1
        Loop
        FileClose(1)
        iIrrigArraySize = iCtr
    End Sub
    'STEP 3: 3rd Level support procedures
    Public Sub LoadSwatVariables() 'Variables used in the LoadSwatVariables
Subroutine.
        Dim iAGRICount As Long 'Counts the number of Records with LULC
        Dim iCount As Long 'Counts the number of Records with LULC of AGRI ()
        Dim lRecordCount As Long 'Counts the number of Records in SWAT file
        Dim iArraySize As Long
        Dim lctr As Long
        Dim sLulcTemp As String
        Dim iHruTemp, iGisTemp, iSubTemp, iMgtTemp, iMonTemp As Integer
        Dim i7, i8, i9, i10, i11, i12, i13, i14, i15, i16, i17, i18, i19,i20, i21,
i22, i23, i24, i25, i26, i27, i28, i29, i30, i31,i32, i33, i34, i35, i36, i37, i38,
i39, i40, i41, i42, i43,i44, i45, i46, i47, i48, i49, i50, i51, i52, i53, i54, i55,
i56, i57, i58, i59, i60, i61, i62, i63, i64, i65, i66, i67, i68, i69, i70, i71, i72,
i73, i74, i75 As Single
        Dim i As Long 'for counter
        Dim lSwatCtr As Long
        Dim bHruCountComplete As Boolean
        Dim sLineRecord As String
        Dim sHeaderLine As String

        iAGRICount = 0
        lRecordCount = 0
        sLulcTemp = "temp"

        bHruCountComplete = False
        iHruCount = 1
        iMoCount = 1

        iArraySize = DataFileLength(sSwatFileName)
        iIrrigArraySize = DataFileLength(sIrrInternalFileName)

        Call ReDimSwatArray(iArraySize)
        Call ReDimRVVariables(iArraySize)

        FileOpen(1, sSwatFileName, OpenMode.Input)
        sHeaderLine = LineInput(1)
        lctr = 0
        Do While Not (EOF(1))
            Input(1, sLulcTemp,iHruTemp,iGisTemp,iSubTemp, iMgtTemp, iMonTemp, i7,
i8, i9, i10, i11, i12, i13, i14, i15, i16, i17, i18, i19,i20, i21, i22, i23, i24,
i25, i26, i27, i28, i29, i30, i31, i32, i33, i34, i35, i36, i37, i38, i39, i40, i41,
i42, i43, i44, i45, i46, i47, i48, i49, i50, i51, i52, i53, i54, i55,i56, i57, i58,
i59, i60, i61, i62, i63, i64, i65, i66, i67, i68, i69, i70, i71, i72, i73, i74, i75)

lctr = iCount 'list this downward.
sLulc(lctr) = sLulcTemp,iHru(lctr) = iHruTemp,iGis(lctr) = iGisTemp,iSub(lctr) =
iSubTemp,iMgt(lctr) = iMgtTemp, iMon(lctr) = iMonTemp,sArea(lctr) = i7,sPrecip(lctr)
= i8,sSnoFall(lctr) = i9, sSnoMelt(lctr) = i10,sIrr(lctr) = i11,sPet(lctr) = i12,
sAEt(lctr) = i13, SW_Init(lctr) = i14,SW_End(lctr) = i15, sPerc(lctr) = i16,
```

```
sGw_Rchg(lctr) = i17,sDa_Rchg(lctr) = i18,Revap(lctr) = i19,sSa_Irr(lctr) = i20,
sDa_Irr(lctr) = i21,sSa_St(lctr) = i22,sDa_St(lctr) = i23,sSurq_Gen(lctr) = i24,
sSurq_Cnt(lctr) = i25,sTLoss(lctr) = i26,sLatq(lctr) = i27,sGwQ(lctr) = i28,
sWYld(lctr) = i29,sDailycn(lctr) = i30,sTmp_AVdgc(lctr) = i31,
sTmp_MXdgc(lctr) = i32,sTmp_MNdgc(lctr) = i33,sOl_Tmpdgcs(lctr) = i34,
sOlArmj(lctr) = i35,sSYld(lctr) = i36,sUsle(lctr) = i37,sN_App(lctr) = i38,
sP_App(lctr) = i39,sNaUto(lctr) = i40,sUto(lctr) = i41,sNgrz(lctr) = i42,
sPgrz(lctr) = i43,sFrtPc(lctr) = i44,sFrtNr(lctr) = i45,sAin(lctr) = i46,
sNfix(lctr) = i47,sFMn(lctr) = i48,sAMn(lctr) = i49,sASn(lctr) = i50,
sFMp(lctr) = i51,sNameNum(lctr) = i52,sLAP(lctr) = i53,sASP(lctr) = i54,
sDNit(lctr) = i55,sNUP(lctr) = i56,sPUP(lctr) = i57,sORGN(lctr) = i58,
sORGP(lctr) = i59,sSEDP(lctr) = i60,sURQ(lctr) = i61,sATQ(lctr) = i62,
sNO3(lctr) = i63,s3GW(lctr) = i64,sSOLP(lctr) = i65,sPGW(lctr) = i66,
sWSTRS(lctr) = i67,sTMP_STRS(lctr) = i68,sN_STRS(lctr) = i69,
sP_STRS(lctr) = i70,sBIOM(lctr) = i71,sLAI(lctr) = i72,sYLD(lctr) = i73,
sBACTP(lctr) = i74,sBACTLP(lctr) = i75

            iETDif(lctr) = sPet(lctr) - sAEt(lctr)
            iCount = iCount + 1
            lRecordCount += 1
            If lctr <> 0 Then
                If (iHru(lctr) > iHru(lctr - 1)) And (iMoCount = 1) Then
                    iHruCount += 1
                Else : bHruCountComplete = True
                End If
                If (iHru(lctr) < iHru(lctr - 1)) Then
                    iMoCount += 1
                Else : End If
            Else : End If
            lctr = lctr + 1
        Loop
        FileClose(1) 'closes Temp SWAT input txt file

        sAvgAreaHRU = sTotAreaAGRIWat / iHruCount
        iCount = iCount - 1
        iSwatArraySize = iCount

        For i = 0 To iSwatArraySize

            sTimeStepYld(i) = sYLD(i)

        Next i
        FileClose(1) 'closes Temp SWAT input txt file
        FileClose(1) 'closes Temp SWAT input txt file
    End Sub
    'STEP 3: 3rd Level support procedures
    Public Sub LoadSwatVariablesMax()
        'Variables used in the LoadSwatVariables Subroutine.
        Dim iAGRICount As Long 'Counts the number of Records with LULC
        Dim iCount As Long 'Counts the number of Records with LULC of AGRI ()
        Dim lRecordCount As Long 'Counts the number of Records in SWAT file
        Dim iArraySize As Long
        Dim lctr As Long
        'Dim iMsgVariable As Integer
        Dim sLulcTemp As String
        Dim iHruTemp, iGisTemp, iSubTemp, iMgtTemp, iMonTemp As Integer
        Dim i7, i8, i9, i10, i11, i12, i13, i14, i15, i16, i17, i18, i19,i20, i21,
i22, i23, i24, i25, i26, i27, i28, i29, i30, i31,i32, i33, i34, i35, i36, i37, i38,
i39, i40, i41, i42, i43,i44, i45, i46, i47, i48, i49, i50, i51, i52, i53, i54, i55,
i56, i57, i58, i59, i60, i61, i62, i63, i64, i65, i66, i67, i68, i69, i70, i71, i72,
i73, i74, i75 As Single
        Dim i As Long 'for counter
        Dim lSwatCtr As Long
        Dim bHruCountComplete As Boolean
        'Dim sLineRecord As String
        Dim sHeaderLine As String
        iAGRICount = 0
        lRecordCount = 0
```

```
        sLulcTemp = "temp"
        bHruCountComplete = False
        iHruCount = 1
        iMoCount = 1
        iArraySize = DataFileLength(sSwatFileName)
        iIrrigArraySize = DataFileLength(sIrrInternalFileName)
        FileOpen(1, sSwatFileName100Irr, OpenMode.Input)
        sHeaderLine = LineInput(1)
        lctr = 0
        Do While Not (EOF(1))
            Input(1, "sLulcTemp, iHruTemp, iGisTemp, iSubTemp, iMgtTemp,iMonTemp,i7,
i8, i9, i10, i11, i12, i13, i14, i15, i16, i17, i18, i19, i20, i21, i22, i23, i24,
i25, i26, i27, i28, i29, i30, i31, i32, i33, i34, i35, i36, i37, i38, i39, i40, i41,
i42, i43, i44, i45, i46, i47, i48, i49, i50, i51, i52, i53, i54, i55, i56, i57, i58,
i59, i60, i61, i62, i63, i64, i65, i66, i67, i68, i69, i70, i71, i72, i73, i74, i75
()")

lctr = iCount 'list this downward.
sLulc(lctr) = sLulcTemp,iHru(lctr) = iHruTemp,iGis(lctr) = iGisTemp,iSub(lctr) =
iSubTemp,iMgt(lctr) = iMgtTemp, iMon(lctr) = iMonTemp,sArea(lctr) = i7,sPrecip(lctr)
= i8,sSnoFall(lctr) = i9, sSnoMelt(lctr) = i10,sIrr(lctr) = i11,sPet(lctr) = i12,
sAEt(lctr) = i13, SW_Init(lctr) = i14,SW_End(lctr) = i15, sPerc(lctr) = i16,
sGw_Rchg(lctr) = i17,sDa_Rchg(lctr) = i18,Revap(lctr) = i19,sSa_Irr(lctr) = i20,
sDa_Irr(lctr) = i21,sSa_St(lctr) = i22,sDa_St(lctr) = i23,sSurq_Gen(lctr) = i24,
sSurq_Cnt(lctr) = i25,sTLoss(lctr) = i26,sLatq(lctr) = i27,sGwQ(lctr) = i28,
sWYld(lctr) = i29,sDailycn(lctr) = i30,sTmp_AVdgc(lctr) = i31,
sTmp_MXdgc(lctr) = i32,sTmp_MNdgc(lctr) = i33,sOl_Tmpdgcs(lctr) = i34,
sOlArmj(lctr) = i35,sSYld(lctr) = i36,sUsle(lctr) = i37,sN_App(lctr) = i38,
sP_App(lctr) = i39,sNaUto(lctr) = i40,sUto(lctr) = i41,sNgrz(lctr) = i42,
sPgrz(lctr) = i43,sFrtPc(lctr) = i44,sFrtNr(lctr) = i45,sAin(lctr) = i46,
sNfix(lctr) = i47,sFMn(lctr) = i48,sAMn(lctr) = i49,sASn(lctr) = i50,
sFMp(lctr) = i51,sNameNum(lctr) = i52,sLAP(lctr) = i53,sASP(lctr) = i54,
sDNit(lctr) = i55,sNUP(lctr) = i56,sPUP(lctr) = i57,sORGN(lctr) = i58,
sORGP(lctr) = i59,sSEDP(lctr) = i60,sURQ(lctr) = i61,sATQ(lctr) = i62,
sNO3(lctr) = i63,s3GW(lctr) = i64,sSOLP(lctr) = i65,sPGW(lctr) = i66,
sWSTRS(lctr) = i67,sTMP_STRS(lctr) = i68,sN_STRS(lctr) = i69,
sP_STRS(lctr) = i70,sBIOM(lctr) = i71,sLAI(lctr) = i72,sYLD(lctr) = i73,
sBACTP(lctr) = i74,sBACTLP(lctr) = i75

            iCount += 1
            iETDiffMax(lctr) = sAEtMax(lctr) - sAEt(lctr)
            lRecordCount += 1
            If (sIrrMax(lctr) <> 0) And (sAEt(lctr) <> sAEtMax(lctr)) Then
                sSwatIrrEff(lctr) = (sAEtMax(lctr) - sAEt(lctr)) / sIrrMax(lctr)
            Else
                sSwatIrrEff(lctr) = 1
            End If
            lctr = lctr + 1
        Loop
        FileClose(1)  'closes Temp SWAT input txt file
        iCount = iCount - 1
        iSwatArraySize = iCount
         For i = 0 To iSwatArraySize

            sTimeStepYldMax(i) = sYldMax(i)
        Next i

    End Sub
    'STEP 3: 4th Level Support Procedures
    Public Sub ReDimSwatArray(ByVal iArraySize As Long)
        'Swat Variables read from the Swat simulation with WOI.
        ReDim lAGRICtr to sFrtNr (iArraySize) 'ReDim Each of SWAT Variables
        'Variables read from Swat Simulation with irrigation
        ReDim sAEtMax(iArraySize)
        ReDim sIrrMax(iArraySize)
        ReDim sYldMax(iArraySize)
        ReDim sTimeStepYldMax(iArraySize)
        ReDim sSwatIrrEff(iArraySize)
```

```
    ReDim iETDiffMax(iArraySize)
    ReDim sTimeStepPotentialYld(iArraySize)
    ReDim sOptYldNew(iArraySize)
End Sub
'STEP 3: 4th Level Support Procedures
Public Sub ReDimRVVariables(ByVal iArraySize As Long)
    ReDim sAppliedIrrSub(iArraySize * 3)
    ReDim sTargetET(iArraySize * 3)
    ReDim sIrrDepth(iArraySize * 3)
    ReDim sIrrVol(iArraySize * 3)
    ReDim sRevenueWOI(iArraySize * 3)
    ReDim sYldDivisor(iArraySize * 3)
    ReDim sRevenue1(iArraySize * 3)
    ReDim sTargetYld(iArraySize * 3)
    ReDim sTimeStepCalcPotentialYld(iArraySize * 3)
    ReDim sTimeStepCalcActYld(iArraySize * 3)
    ReDim sRatioTetPet(iArraySize * 3)
    ReDim sRatioTetMet(iArraySize * 3)
    ReDim sTimeStepYld(iArraySize)
    'Corresponding Net Revenue Variables listed below.
    ReDim sOptIrrDepth(iArraySize * 3)
    ReDim sOptIrrVol(iArraySize * 3)
    ReDim sMaxRevenueWI(iArraySize * 3)
    ReDim sMaxRevenueWOI(iArraySize * 3)
    ReDim sMaxRevenueDif(iArraySize * 3)
    ReDim sOptActIrrYld(iArraySize * 3)
    ReDim sOptActIrrET(iArraySize * 3)
End Sub
'STEP 3: 4th Level Support Procedures
Public Sub ReDimRVRecVariables()
    'ReDims Values used in determining Best irrigation
    ReDim sSub2RVWOIYr(iNumHru * 3)
    ReDim sSub2RVWIYr(iNumHru * 3)
    ReDim sSub2RVDifYr(iNumHru * 3)
    ReDim bSub2RecYr(iNumHru * 3)
    ReDim sSub5RVWOIYr(iNumHru * 3)
    ReDim sSub5RVWIYr(iNumHru * 3)
    ReDim sSub5RVDifYr(iNumHru * 3)
    ReDim bSub5RecYr(iNumHru * 3)
    ReDim sSub24RVWOIYr(iNumHru * 3)
    ReDim sSub24RVWIYr(iNumHru * 3)
    ReDim sSub24RVDifYr(iNumHru * 3)
    ReDim bSub24RecYr(iNumHru * 3)
    ReDim sRecIrrSub(iNumHru * 3)
    ReDim sTotIrrVolSubYr(iNumHru * 3)
    ReDim iRecIrrSubInt(iNumHru * 3)
    ReDim sSub2IrrVolYr(iNumHru * 3)
    ReDim sSub5IrrVolYr(iNumHru * 3)
    ReDim sSub24IrrVolYr(iNumHru * 3)
    ReDim sRVMaxDif(iNumHru * 3)
End Sub
'STEP 3: 4th Level Support Procedures
Public Sub ReDimHruSummary()
    Dim i As Long
    Dim iNumMoHruValues As Integer

    iNumHru = 1
    sTotAreaAGRIWat = sArea(0)
    For i = 1 To iSwatArraySize
        If iHru(i) > iHru(i - 1) Then
            iHruHigh = iHru(i)
            iNumHru = iNumHru + 1
            sTotAreaAGRIWat = sTotAreaAGRIWat + sArea(i)
        Else : Exit For
        End If
    Next i
    iNumMoHruValues = iNumHru * 12
    'ReDims the General Summary Tables.
```

```
    ReDim iHruHruSum(iNumHru)
    ReDim iSubHruSum(iNumHru)
    ReDim sAvgIrrDHruMo(iNumHru)
    ReDim sAvgIrrDHruYr(iNumHru)
    ReDim sAvgIrrVHruMo(iNumHru)
    ReDim sAvgIrrVHruYr(iNumHru)
    ReDim sAvgIrrRVWIHruMo(iNumHru)
    ReDim sAvgIrrRVWIHruYr(iNumHru)
    ReDim sAvgIrrRVWOIHruMo(iNumHru)
    ReDim sAvgIrrRVWOIHruYr(iNumHru)
    ReDim sAvgIrrRVDifHruYr(iNumHru)
    ReDim sAvgIrrRecHruYr(iNumHru)
    'ReDims the Monthly Summary Tables.
    ReDim iMoHruHruSum(iNumMoHruValues)
    ReDim iMoSubHruSum(iNumMoHruValues)
    ReDim iMoMonHruSum(iNumMoHruValues)
    ReDim sMoAvgIrrDHruMo(iNumMoHruValues)
    ReDim sMoAvgIrrDHruYr(iNumMoHruValues)
    ReDim sMoAvgIrrVHruMo(iNumMoHruValues)
    ReDim sMoAvgIrrVHruYr(iNumMoHruValues)
    ReDim sMoAvgRVWIHruMo(iNumMoHruValues)
    ReDim sMoAvgRVWOIHruMo(iNumMoHruValues)
End Sub
'STEP 3: 4th Level Support Procedures
Public Sub ReDimSubSummary()
    Dim i As Long
    Dim iNumMoSubValues As Long
    iNumSub = 0
    For i = 1 To iSwatArraySize

        If iSub(i) > iSub(i - 1) Then
            iSubHigh = iSub(i)
            iNumSub = iNumSub + 1
        Else : End If
    Next i
    iNumMoSubValues = iNumSub * 12
    'ReDims the general summary arrays for each subbasin.
    ReDim iHruSubSum(iSubHigh)
    ReDim iSubSubSum(iSubHigh)
    ReDim sAvgIrrDSubMo(iSubHigh)
    ReDim sAvgIrrDSubYr(iSubHigh)
    ReDim sAvgIrrVSubMo(iSubHigh)
    ReDim sAvgIrrVSubYr(iSubHigh)
    ReDim sAvgIrrRVWISubMo(iSubHigh)
    ReDim sAvgIrrRVWISubYr(iSubHigh)
    ReDim sAvgIrrRVWOISubMo(iSubHigh)
    ReDim sAvgIrrRVWOISubYr(iSubHigh)

    'ReDims the Monthly summary arrays for each subbasin.
    ReDim iMoHruSubSum(iNumMoSubValues)
    ReDim iMoSubSubSum(iNumMoSubValues)
    ReDim iMoMonSubSum(iNumMoSubValues)
    ReDim sMoAvgIrrDSubMo(iNumMoSubValues)
    ReDim sMoAvgIrrDSubYr(iNumMoSubValues)
    ReDim sMoAvgIrrVSubMo(iNumMoSubValues)
    ReDim sMoAvgIrrVSubYr(iNumMoSubValues)
    ReDim sMoAvgRVWISubMo(iNumMoSubValues)
    ReDim sMoAvgRVWOISubMo(iNumMoSubValues)
    ReDim iMoHruSubSum(iNumMoSubValues)
End Sub
'STEP 3: 4th Level Support Procedures
Public Sub CalculateRevenue(ByVal iIrrType As Integer)
    'General Counter variables used below
    Dim iIrrCtr As Integer 'counter for Irrig array variables
    Dim i As Long 'Loop counter for printing of at end of routine
    Dim j As Integer 'counter for the number of irrigation records()

    Call OpenGenOutPutPrintFiles()
```

```
        If iIrrType = 10 Then
            For j = 0 To 0
                iIrrCtr = j

                Call OpenRVPrintFiles(iIrrCtr)
                Call RunRVCalculations(iIrrCtr)
                Call CloseRVPrintFiles()
            Next j
            'Close()
        Else : iIrrCtr = iIrrType
            Call OpenRVPrintFiles(iIrrCtr)
            Call RunRVCalculations(iIrrCtr)
            Call CloseRVPrintFiles()
            Close()
        End If
        'This routine checks that the actual yield calcuated by SWAT is equal to the
yield calculated assuming no irrigation
        FileOpen(100, "D:\Documents and settings\kassa\My documents\Visual Studio
2008\IWAT OUTPUT\100 CheckActualYields.txt", OpenMode.Output)
        PrintLine(100, "The yield reported in the first column is the yield reported
by SWAT with no Irrigation")
        PrintLine(100, "The yield reported in the second and third column is the
yield calculated using the deficit irrigation equation using the max yield as that
reported by SWAT with 100% irrigation.")
        PrintLine(100)
        PrintLine(100)
        PrintLine(100, "Sub", "HRU", "ActSWATYld, CalcActYld, MaxSWATYld,
CalcPotYld, sAET, sAETMax")

        For i = 0 To iSwatArraySize
            PrintLine(100, iSub(i), iHru(i), sTimeStepYld(i),
sTimeStepCalcActYld(i), sTimeStepYldMax(i), sTimeStepCalcPotentialYld(i), sAEt(i),
sAEtMax(i))
        Next i
        FileClose(100)
        FileClose(21)
    End Sub
    'STEP 3: 4th Level Support Procedures
    Public Sub OpenGenInputPrintFiles()
        Dim sTempLineInput As String

        FileOpen(21, "D:\Visual basic_data\ModelOutputFiles\ 21_TempRVDataFile.txt",
OpenMode.Input)
        sTempLineInput = LineInput(21)

    End Sub
    '    'STEP 3: 4th Level Support Procedures
    Public Sub OpenGenOutPutPrintFiles()
        FileOpen(21, "D:\Visual basic_data\ModelOutputFiles\21_TempRVDataFile.txt",
OpenMode.Output)
        'PrintLine(21, "IrrCtr", "HRU", "Irr_sub", "Avg.Yr.RV.WOI", "Avg.Yr.RV.WI",
"Avg.Yr.RV.Dif.", "Avg.Yr.IrrV")
        PrintLine(21, "IrrCtr, HRU, Irr_sub, Avg.Yr.RV.WOI, Avg.Yr.RV.WI,
Avg.Yr.RV.Dif., Avg.Yr.IrrV")

        FileOpen(20, "D:\Visual basic_data\ModelOutputFiles\20_RVCalcTempFile.txt",
OpenMode.Output)
        PrintLine(20, "HRU", "RVCPWI", "RVCPWOI", "RVCPDif", "RVTGWI", "RVTGWOI",
"RVTGDif", "RVSub24WI", "RVSub24WOI", "RVSub24Dif")
        FileClose(20)
        'The following opens the files to be written to during the course of the
calculations.
        FileOpen(111, "D:\Documents and settings\kassa\My documents\Visual Studio
2008\IWAT OUTPUT\111_NewIrrigVol.txt", OpenMode.Output)
        FileOpen(1, "D:\Visual
basic_data\ModelOutputFiles\01_TargetETEqVariables.txt", OpenMode.Output)
```

```
        FileOpen(2, "D:\Visual
basic_data\ModelOutputFiles\02_IrrVolEqVariables.txt", OpenMode.Output)
        FileOpen(3, "D:\Documents and settings\kassa\My documents\Visual Studio
2008\IWAT OUTPUT\02_Yield_Revenue.txt", OpenMode.Output)
        FileOpen(4, "D:\Documents and settings\kassa\My documents\Visual Studio
2008\IWAT OUTPUT\01_AllResults.txt", OpenMode.Output)
        FileOpen(5, "D:\Visual
basic_data\ModelOutputFiles\05_RevenueEqVariablesAbb.txt", OpenMode.Output)
        FileOpen(6, "D:\Documents and settings\kassa\My documents\Visual Studio
2008\IWAT OUTPUT\06_ModelRecResults.txt", OpenMode.Output)
        FileOpen(7, "D:\Documents and settings\kassa\My documents\Visual Studio
2008\IWAT OUTPUT\07_TimeStepYldTempFile.txt", OpenMode.Output)
        PrintLine(111, "i", "HRU", "SUB", "LULC", "Iteration", "ActYld(t/ha)",
"TargetYld", "MaxSwatYld", "ActET(mm)", "TargetET(mm)", "MaxAET", "Area(km^2)",
"RevenueTarget", "RevenueDiff", "ProdMax", "ProdTarg", "ProdDiff", "IrrVolDiff")
        PrintLine(3, "i", "HRU", "SUB", "LULC", "Year", "Iteration", "ActYld(t/ha)",
"TargetYld", "MaxSwatYld", "Ky", "ActET(mm)", "TargetET(mm)", "MaxAET", "PotET(mm)",
"Area(km^2)", "RevenueDiff", "ProdMax", "ProdTarg", "ProdDiff")
        PrintLine(4, "i", "HRU", "SUB", "LULC", "Year", "Iteration", "OPtIrrDepth",
"maxIrrDepth", "ActET(mm)", "TargetET(mm)", "MaxAET", "YldDivisor", "PotET(mm)",
"IrrVol", "CalcNetB", "ChangeYld", "Revenuecrop")

        PrintLine(6, "i", "j", "k", "HRU", "SUB", "LULC", "Month", "OptIteration",
"IrrSub", "OptIrrDepth", "OptIrrVol", "OptActIrrYld", "OptActIrrET", "MaxRevenueWI")

        PrintLine(7, "HRU", "Month", "ActYTDYield", "TimeStepYield", "TargetYld",
"MaxYld", "PotentialCalcYld")

    End Sub
    'STEP 3: 4th Level Support Procedures
    Public Sub OpenRVPrintFiles(ByVal iIrrCtr As Integer)
        Dim sOptIrrSchedFileName As String
        Dim sRecIrrSubFileName As String

        sOptIrrSchedFileName = "D:\Documents and settings\kassa\My documents\Visual
Studio 2008\IWAT OUTPUT\22_OptimalIrrSched.txt_" & sIrrSub(iIrrCtr) & ".txt"
        sRecIrrSubFileName = "D:\Documents and settings\kassa\My documents\Visual
Studio 2008\IWAT OUTPUT\23_RecIrrSub_" & sIrrSub(iIrrCtr) & ".txt"
        FileOpen(22, sOptIrrSchedFileName, OpenMode.Output)
        FileOpen(23, sRecIrrSubFileName, OpenMode.Output)
        PrintLine(22)
        PrintLine(22, "For irrigation ID: ", sIrrSub(iIrrCtr))
        PrintLine(22, "Sub, HRU, Month, IrrSub, OptIrrDepth, OptIrrVol, Ratio
TET/MET, TargetET, TargetYld")
        PrintLine(23)
        PrintLine(23, "For irrigation ID: ", sIrrSub(iIrrCtr))
        PrintLine(23, "Sub", "HRU", "Month", "IrrSub", "RV: W/O Irrig", "RV:
W/Irrig") 'Opens General output tables)
        FileOpen(9, "D:\Documents and settings\kassa\My documents\Visual Studio
2008\IWAT OUTPUT\09_HRUSumMoData_" & sIrrSub(iIrrCtr) & ".txt", OpenMode.Output)
        FileOpen(10, "D:\Documents and settings\kassa\My documents\Visual Studio
2008\IWAT OUTPUT\10_SubSumMoData_" & sIrrSub(iIrrCtr) & ".txt", OpenMode.Output)
        FileOpen(11, "D:\Documents and settings\kassa\My documents\Visual Studio
2008\IWAT OUTPUT\11_WatSumMoData_" & sIrrSub(iIrrCtr) & ".txt", OpenMode.Output)
        FileOpen(12, "D:\Documents and settings\kassa\My documents\Visual Studio
2008\IWAT OUTPUT\12_HRUSumYrData_" & sIrrSub(iIrrCtr) & ".txt", OpenMode.Output)
        FileOpen(13, "D:\Documents and settings\kassa\My documents\Visual Studio
2008\IWAT OUTPUT\13_SubSumYrData_" & sIrrSub(iIrrCtr) & ".txt", OpenMode.Output)
        FileOpen(14, "D:\Documents and settings\kassa\My documents\Visual Studio
2008\IWAT OUTPUT\14_WatSumYrData_" & sIrrSub(iIrrCtr) & ".txt", OpenMode.Output)
        PrintLine(9, "Irr_Sub", "Sub", "HRU", "Avg.Mo.IrrD", "Avg.Mo.IrrV",
"Avg.Mo.RV.WOI", "Avg.Mo.RV.WI")
        PrintLine(10, "Irr_Sub", "Sub", "Avg.Mo.IrrD", "Avg.Mo.IrrV",
"Avg.Mo.RV.WOI", "Avg.Mo.RV.WI")
        PrintLine(11, "Irr_Sub", "Avg.Mo.IrrD", "Avg.Mo.IrrV", "Avg.Mo.RV.WOI",
"Avg.Mo.RV.WI")
        PrintLine(12, "Irr_Sub", "Sub", "HRU", "Avg.Yr.IrrD", "Avg.Yr.IrrV",
"Avg.Yr.RV.WOI", "Avg.Yr.RV.WI")
```

```
        PrintLine(13, "Irr_Sub", "Sub", "Avg.YrIrrD", "Avg.Yr.IrrV",
"Avg.Yr.RV.WOI", "Avg.Yr.RV.WI")
        PrintLine(14, "Irr_Sub", "Avg.YrIrrD", "Avg.Yr.IrrV", "Avg.Yr.RV.WOI",
"Avg.Yr.RV.WI")
    End Sub
    ''STEP 3: 4th Level Support Procedures
    Public Sub CloseRVPrintFiles()
        FileClose(22)
        FileClose(23)
        FileClose(9)
        FileClose(10)
        FileClose(11)
        FileClose(12)
        FileClose(13)
        FileClose(14)
    End Sub
    'STEP 3: 4th Level Support Procedures
    Public Function SetEconCtr(ByVal lSwatCtr As Long)   'As string newly added
        Dim k As Integer 'For Loop counter this runs through the econ data loaded
and selects the crop type  associatd with HRU

        For k = 0 To 4
            If sEconIdCrop(k) = sLulc(lSwatCtr) Then
                SetEconCtr = k
                Exit For
            Else : End If
        Next k
        SetEconCtr = k
    End Function

    'STEP 3: 4th Level Support Procedures
    Public Function SetMaxETDif() 'ByVal iArraySize As Long) 'As ByVal lSwatCtr As
Long newly added
        Dim i As Long 'counter
        Dim iMaxETDif As Integer
        iMaxETDif = 0

        For i = 0 To iSwatArraySize
            If iETDif(i) > iMaxETDif Then
                iMaxETDif = iETDif(i)
            Else : End If
        Next i
        SetMaxETDif = iMaxETDif
    End Function

    ''STEP 3: 4th Level Support Procedures
    Public Sub RunRVCalculations(ByVal iIrrCtr As Integer)
        Dim lSwatCtr As Long 'counter for Swat array variables
        Dim iEconCtr As Integer  'counter for Econ array variables
        Dim iItCtr As Long 'counter for repetative iterations
        Dim i As Long 'counter for number of SWAT data records
        Dim j As Long 'counter for the irrigation being calculated.
        Dim k As Integer 'counter for the number of economic data records

        'The following are Temp arrays that are used during the iteration process to
hold temporary values during RV calculations
        Dim sRevenueWOIHolder As Single
        Dim sTargetETTemp() As Single
        Dim sIrrDepthTemp() As Single
        Dim sIrrVolTemp() As Single 'This is being calculated in units of m^3/ha
        Dim sIrrVolMax() As Single 'This is being calculated in units of m^3/ha
        Dim sRevenueTarget() As Single
        Dim sAreaShareTemp() As Single
        Dim sRevenueWOITemp() As Single
        Dim sYldDivisorTemp() As Single ' this value is the value the Yield is
divided by in the equation above
        Dim sRevenueTemp1() As Single
        Dim sRatioTetPetTemp() As Single
```

```
        Dim sRatioTetMetTemp() As Single
        Dim sTargetYldTemp() As Single
        Dim iMaxItCtr As Long 'is set equal to the max size of difference between
Potential ET and Actual ET
        Dim iOptIt As Integer 'the iteration at which the greatest net Revenue is
achieved.
        Dim sRevenueTem() As Single 'Holds the value of the Revenue used in teh
determination of Revenue
        Dim sChangeYld() As Single   'Holds the value of the Revenue used in teh
determination of Revenue
        'Dim sqrt As Single 'Holds the value of the Revenue used in teh
determination of Revenue
        Dim sProductivityMax() As Single
        Dim sProductivityTarg() As Single
        Dim sProductivityDiff() As Single
        Dim sIrrigVolDiff() As Single
        Dim sIrrVol1() As Single
        Dim sIrrVolTarget() As Single
        iMaxItCtr = SetMaxETDif()
        'the following ReDims the Temp arrays to the size of the AGRI data file.
        ReDim sTargetETTemp(iMaxItCtr)
        ReDim sIrrDepthTemp(iMaxItCtr)
        ReDim sIrrVolTemp(iMaxItCtr)
        ReDim sIrrVolMax(iMaxItCtr)
        ReDim sRevenueWOITemp(iMaxItCtr)
        ReDim sYldDivisorTemp(iMaxItCtr)
        ReDim sRevenueTemp1(iMaxItCtr)
        ReDim sRevenueTarget(iMaxItCtr)
        ReDim sAreaShareTemp(iMaxItCtr)
        ReDim sRatioTetPetTemp(iMaxItCtr)
        ReDim sRatioTetMetTemp(iMaxItCtr)
        ReDim sTargetYldTemp(iMaxItCtr)
        ReDim sRevenueTem(iMaxItCtr)
        ReDim sChangeYld(iMaxItCtr)
        ReDim sProductivityMax(iMaxItCtr)
        ReDim sProductivityTarg(iMaxItCtr)
        ReDim sProductivityDiff(iMaxItCtr)
        ReDim sIrrigVolDiff(iMaxItCtr)
        ReDim sIrrVol1(iMaxItCtr)
        ReDim sIrrVolTarget(iMaxItCtr)

        For i = 0 To iSwatArraySize

            lSwatCtr = i
            iEconCtr = SetEconCtr(lSwatCtr)
            iItCtr = k
            sIrrDepthTemp(lSwatCtr) = sIrrMax(lSwatCtr)
            Call SetRVParamWI(i, j, k, lSwatCtr, iItCtr, iEconCtr, iIrrCtr)

            iItCtr = iItCtr + 1
            'The following section calculates the net Revenue WOI.
            If sIrrDepthTemp(lSwatCtr) = 0 Then
                sTargetETTemp(iItCtr) = sAEt(lSwatCtr)
            Else
            End If
            If sIrrDepthTemp(lSwatCtr) > 0 Then
                sIrrDepthTemp(iItCtr) = sIrrDepthTemp(lSwatCtr) - 1
            Else : sIrrDepthTemp(iItCtr) = 0
            End If

'The following section calculates the net Revenue with full irrigation . It is has
to be copied and pasted for the number of crops exist to treat  individually based
on the limiting factors.

            For k = 1 To 100

                If sIrrDepthTemp(lSwatCtr) > 0 Then
```

```
                    sTargetETTemp(iItCtr) = (sAEtMax(lSwatCtr) *
sIrrDepthTemp(lSwatCtr)) / sIrrMax(lSwatCtr)
                Else : sTargetETTemp(iItCtr) = sAEt(lSwatCtr)
                End If

                If sYldMax(lSwatCtr) > 0 Then
                    sTargetYldTemp(iItCtr) = sYldMax(lSwatCtr) * (1 -
(sEconKy(iEconCtr) * (1 - (sTargetETTemp(iItCtr) / sAEtMax(lSwatCtr)))))

                Else : sTargetYldTemp(iItCtr) = 0
                End If

                sIrrVolMax(iItCtr) = (sIrrMax(iItCtr) * 10) / (sIrrEff(iIrrCtr))

                sIrrVolTemp(iItCtr) = (sIrrDepthTemp(iItCtr) * 10) /
(sIrrEff(iIrrCtr))
                sYldDivisorTemp(iItCtr) = (1 - sEconKy(iEconCtr) * (1 -
(sTargetETTemp(iItCtr) / sAEtMax(lSwatCtr))))


                'The following two equations determine the actual yield and maximum
yield using the original yield equation.

                sTimeStepCalcPotentialYld(lSwatCtr) = sTimeStepYld(lSwatCtr) / (1 -
(sEconKy(iEconCtr) * (1 - (sAEt(lSwatCtr) / sAEtMax(lSwatCtr)))))
                sTimeStepCalcActYld(lSwatCtr) = sTimeStepYldMax(lSwatCtr) * (1 -
(sEconKy(iEconCtr) * (1 - (sAEt(lSwatCtr) / sAEtMax(lSwatCtr)))))

                sMaxRevenueWOI(lSwatCtr) = sRevenueTem(iItCtr)
                sRevenueWOIHolder = sRevenueTem(iItCtr)

                'This section calcualtes the Revenue with full Irrigation
                sIrrVolTemp(iItCtr) = (sIrrDepthTemp(iItCtr) * 10) /
(sIrrEff(iIrrCtr))
                sYldDivisorTemp(iItCtr) = 1 - (sEconKy(iEconCtr) * (1 -
(sAEt(lSwatCtr) / sTargetETTemp(iItCtr))))

                If iMon(lSwatCtr) > 12 And sTimeStepYldMax(lSwatCtr) > 0 Then
                    sRevenueMaxTemp(iItCtr) = sEconPCrop(iEconCtr) *
(sTimeStepYldMax(lSwatCtr)

                Else : sRevenueTemp1(iItCtr) = 0
                End If

                If iHru(lSwatCtr) = 14 And iMon(lSwatCtr) > 12 Then

                    Do
                        If sIrrDepthTemp(iItCtr) > 0 Then
                            sIrrDepthTemp(iItCtr) = sIrrDepthTemp(iItCtr) - 1
                        Else : sIrrDepthTemp(iItCtr) = 0
                        End If

                        If sIrrDepthTemp(iItCtr) > 0 Then
                            sTargetETTemp(iItCtr) = (sAEtMax(lSwatCtr) *
sIrrDepthTemp(iItCtr)) / sIrrMax(lSwatCtr)
                        Else : sTargetETTemp(iItCtr) = sAEt(lSwatCtr)
                        End If
                        If sYldMax(lSwatCtr) > 0 Then
                            sTargetYldTemp(iItCtr) = sYldMax(lSwatCtr) * (1 -
(sEconKy(iEconCtr) * (1 - (sTargetETTemp(iItCtr) / sAEtMax(lSwatCtr)))))

                        Else : sTargetYldTemp(iItCtr) = 0
                        End If
                        If sYldMax(lSwatCtr) > 0 Then
                            sRevenueTemp(iItCtr)= (sEconPCrop(iEconCtr)*
                          sYldMax(lSwatCtr)* sYldDivisorTemp(iItCtr)
                          sChangeRevenueTemp1(iItCtr) = (sEconPCrop(iEconCtr) *
                          (sYldMax(lSwatCtr) - sTargetYldTemp(iItCtr)) *
```

```
                            (sYldMax(lSwatCtr) - sTargetYldTemp(iItCtr))) /
                            sYldMax(lSwatCtr)
                        Else : sRevenueTem(iItCtr) = 0
                        End If
                        If iMon(lSwatCtr) > 12 Then
                            sChangeYld(iItCtr) = sTimeStepYldMax(lSwatCtr) -
sTargetYldTemp(iItCtr)
                        Else : sChangeYld(iItCtr) = 0
                        End If

                        If sIrrVolMax(iItCtr) > 0 Then
                            sProductivityMax(iItCtr) = (100 * sYldMax(lSwatCtr)) /
(sIrrVolMax(iItCtr))
                        Else
                        End If
                        If sIrrVolTemp(iItCtr) > 0 Then
                            sProductivityTarg(iItCtr) = (100 *
sTargetYldTemp(iItCtr)) / (sIrrVolTemp(iItCtr))
                        Else
                        End If
                        sProductivityDiff(iItCtr) = sProductivityTarg(iItCtr) -
sProductivityMax(iItCtr)
                        If sRevenueTemp(iItCtr-1) > 0.92(sRevenueMaxTemp(iItCtr))
Then
                            Exit Do
                        Else : End If

                  Loop While sRevenueTemp(iItCtr-1) <= 0.92(sRevenueMaxTemp(iItCtr))

                    PrintLine(111, i, iHru(lSwatCtr), iSub(lSwatCtr),
sLulc(lSwatCtr), k, sYLD(lSwatCtr), sTargetYldTemp(iItCtr), sYldMax(lSwatCtr),
sAEt(lSwatCtr), sTargetETTemp(iItCtr), sAEtMax(lSwatCtr), sArea(lSwatCtr),
sRevenueTarget(iItCtr), sRevenueTemp1(iItCtr), sProductivityMax(iItCtr),
sProductivityTarg(iItCtr), sProductivityDiff(iItCtr), sIrrigVolDiff(iItCtr))

                    PrintLine(3, i, iHru(lSwatCtr), iSub(lSwatCtr), sLulc(lSwatCtr),
iMon(lSwatCtr), k, sYLD(lSwatCtr), sTargetYldTemp(iItCtr), sYldMax(lSwatCtr),
sEconKy(iEconCtr), sAEt(lSwatCtr), sTargetETTemp(iItCtr), sAEtMax(lSwatCtr),
sPet(lSwatCtr), sArea(lSwatCtr), sRevenueTemp1(iItCtr), sProductivityMax(iItCtr),
sProductivityTarg(iItCtr), sProductivityDiff(iItCtr))
                    PrintLine(4, i, iHru(lSwatCtr), iSub(lSwatCtr), sLulc(lSwatCtr),
iMon(lSwatCtr), k, sIrrDepthTemp(iItCtr), sIrrMax(lSwatCtr), sAEt(lSwatCtr),
sTargetETTemp(iItCtr), sAEtMax(lSwatCtr), sYldDivisorTemp(iItCtr), sPet(lSwatCtr),
sIrrVolTemp(iItCtr), sRevenueTemp1(iItCtr), sChangeYld(iItCtr),
sRevenueTarget(iItCtr))

            If sTargetYldTemp(iItCtr) <> 0 And sTargetYldTemp(iItCtr - 1) >
sTargetYldTemp(iItCtr) Then
            iOptIt = iItCtr - 1
            Else : iOptIt = 0
            End If
            'This if-then statement determine the followingl.
            sOptIrrDepth(lSwatCtr) = sIrrDepthTemp(iOptIt)
            sOptIrrVol(lSwatCtr) = sIrrVolTemp(iOptIt)
            sRatioTetPetTemp(iOptIt) = sTargetETTemp(iOptIt) / sPet(lSwatCtr)
            sRatioTetMetTemp(iOptIt) = sTargetETTemp(iOptIt) / sAEtMax(lSwatCtr)
            sOptActIrrYld(lSwatCtr) = sTargetYldTemp(iOptIt)
            sOptActIrrET(lSwatCtr) = sTargetETTemp(iOptIt)
            sMaxRevenueWI(lSwatCtr) = sRevenueTemp1(iOptIt)
            sTargetET(i) = sTargetETTemp(iOptIt)
            sIrrDepth(i) = sIrrDepthTemp(iOptIt)
            sIrrVol(i) = sIrrVolTemp(iOptIt)
            sYldDivisor(i) = sYldDivisorTemp(iOptIt)
            sRevenue1(i) = sRevenueTemp1(iOptIt)
            sTargetYld(i) = sTargetYldTemp(iOptIt)
            sRatioTetPet(i) = sRatioTetPetTemp(iOptIt)
            sRatioTetMet(i) = sRatioTetMetTemp(iOptIt)
```

```
            PrintLine(6, i, j, k, iHru(lSwatCtr), iSub(lSwatCtr), sLulc(lSwatCtr),
iMon(lSwatCtr), iOptIt, sIrrSub(iIrrCtr), sOptIrrDepth(lSwatCtr),
sOptIrrVol(lSwatCtr), sOptActIrrYld(lSwatCtr), sOptActIrrET(lSwatCtr),
sMaxRevenueWI(lSwatCtr))
            PrintLine(7, iHru(lSwatCtr), iMon(lSwatCtr), sYLD(lSwatCtr),
sTimeStepYld(lSwatCtr), sTargetYld(lSwatCtr), sYldMax(lSwatCtr),
sTimeStepCalcPotentialYld(lSwatCtr))

            'Code intended to break the program if the RVdif gets to be too high.
            sMaxRevenueDif(lSwatCtr) = sMaxRevenueWI(lSwatCtr) -
sMaxRevenueWOI(lSwatCtr)

        Next i

        Call GenerateOutputTables(iIrrCtr) 'Prints Irrigation Depth/Volume and Net
Revenue Values.
    End Sub

    'STEP 3: 4th Level Support Procedures
    Public Sub SetRVParamWOI(ByVal i As Long, ByVal j As Long, ByVal k As Integer,
ByVal lSwatCtr As Long, ByVal iItCtr As Integer, ByVal iEconCtr As Integer, ByVal
iIrrCtr As Integer)
    End Sub
    'STEP 3: 4th Level Support Procedures
    Public Sub SetRVParamWI(ByVal i As Long, ByVal j As Long, ByVal k As Integer,
ByVal lSwatCtr As Long, ByVal iItCtr As Integer, ByVal iEconCtr As Integer, ByVal
iIrrCtr As Integer)
    End Sub

    'STEP 3: 4th Level Support Procedures
    Public Sub GenerateOutputTables(ByVal iIrrCtr)
        Dim i As Long 'general counter
        For i = 0 To iSwatArraySize
            PrintLine(22, iSub(i), iHru(i), iMon(i), sIrrSub(iIrrCtr),
sOptIrrDepth(i), sOptIrrVol(i), sRatioTetMet(i), sTargetET(i), sTargetYld(i))
            PrintLine(23, iSub(i), iHru(i), iMon(i), sIrrSub(iIrrCtr),
sMaxRevenueWOI(i), sMaxRevenueWI(i))

        Next i
    End Sub
  #End Region
End Class
```

Appendix 7.5 Monthly ETO Penman-Monteith data

(File: D:\CROPWATW\CLIMATE\CHENCHA35.pEm)

Country: Ethiopia Station: CHENCH35

Altitude: 2680 m. Latitude: 6.15 °N Longitude: 37.38 °E

Month	Min Temp	Max Temp	Humidity	Wind	Sunshine	Radiation	ETo
	°C	°C	%	km/day	hours	MJ/m²/day	mm/day
January	11.7	31.1	58	95	10	22.8	4.57
February	11	32.5	62	104	8.7	22.1	4.79
March	12.5	32.7	65	181	7.5	21.1	5.37
April	12.4	30.7	73	130	7.5	21	4.7
May	12.6	29.6	77	112	7.5	20.3	4.31
June	12.2	28.9	72	104	6.2	17.9	3.89
July	12.5	29.5	70	95	5.6	17.1	3.81
August	12.4	29.4	67	104	5.1	16.9	3.91
September	13.1	31.4	71	86	6.4	19.2	4.23
October	12.3	30.7	71	95	7.6	20.6	4.37
November	11	30.6	69	78	8.8	21.3	4.21
December	10.1	31	60	69	9.2	21.2	4.06
Average	12	30.7	68	104	7.5	20.1	4.35

Appendix 7.6 Sample Irrigation schedueling for the crop Potato

ETo station: CHENCH35 Crop: Potato Planting date: 01/01

Rain station: CHENCHA Soil: Medium Harvest date: 09/05 Yield red.: 0.0 %

Application: Refill to 100 % of field capacity Field eff. 70 % Irrigation method: Furrow

Date	Day	Stage	Rain	Depl	Ks	ETa	NetIr	Deficit	Loss	Gr. Ir	r Flow
			mm	%	fract.	%	mm	mm	mm	mm	l/s/ha
12-Jan	12	A	0	26	1	100	13.4	0	0	19.1	0.18
22-Jan	22	A	0	28	1	100	16.4	0	0	23.5	0.27
01-Feb	32	B	0	29	1	100	19.1	0	0	27.3	0.32
11-Feb	42	B	0	32	1	100	23.7	0	0	33.9	0.39
19-Feb	50	B	0	29	1	100	23.4	0	0	33.4	0.48
26-Feb	57	C	0	31	1	100	25.7	0	0	36.7	0.61
04-Mar	64	C	0	30	1	100	25.5	0	0	36.4	0.6
10-Mar	70	C	0	36	1	100	30.4	0	0	43.4	0.84
18-Mar	78	C	0	30	1	100	25.3	0	0	36.2	0.52
29-Mar	89	C	0	32	1	100	26.6	0	0	38.1	0.4
10-Apr	101	D	0	33	1	100	27.7	0	0	39.6	0.38
10-May	End	D	0	17	1	0					

Total gross irrigation 367.6 mm Total rainfall 436.0 mm

Total net irrigation 257.4 mm Effective rainfall 302.9 mm

Total irrigation losses 0.0 mm Total rain loss 133.1 mm

Actual water use by crop 574.8 mm Moist deficit at harvest 14.5 mm

Potential water use by crop 574.8 mm Actual irrigation requirement 271.9 mm

Efficiency irrigation schedule 100.0 % Efficiency rain 69.5 %

Deficiency irrigation schedule 0.0 %