HYDROLOGICAL MODELING AS A TOOL FOR SUSTAINABLE WATER RESOURCES MANAGEMENT: A CASE STUDY OF THE AWASH RIVER BASIN

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May 2011
ABSTRACT

The growing pressure on the world’s fresh water resources is enforced by population growth that leads to conflicts between demands for different purposes. A main concern on water use is the conflict between the environment and other purposes like hydropower, irrigation for agriculture and domestic and industry water supply, where total flows are diverted without releasing water for ecological conservation. As a consequence, some of the common problems related to water faced by many countries are shortage, quality deterioration and flood impacts. Hence, utilization of integrated water resources management in a single system, which is built up by river basin, is an optimum way to handle the question of water. However, in many areas, when planning for balancing water demands major gaps exist on baseline knowledge of water resources. In order to bridge these gaps, hydrological models are among the available tools used to acquire adequate understanding of the characteristics of the river basin. Apart from forecasting and predicting the quantity and quality of water for decision makers, some models could also help in predicting the impacts of natural and anthropogenic changes on water resources and also in quantifying the spatial and temporal availability of the resources. However, main challenges lie in choosing and utilizing these models for a specific basin and managerial plan. In this study, an analysis of the different types of models and application of a selected model to characterize the Awash River basin, located in Ethiopia, is presented. The results from the modeling procedure and the performance of the model are discussed. The different possible sources of uncertainties in the modeling process are also discussed. The results indicate dissimilar predictions in using different methods; hence proper care must be taken in selecting and employing available methods for a specific watershed prior to presenting the results to decision makers.

Key words: Hydrological characteristics; Distributed hydrological modeling; Rainfall-runoff correlation; Streamflow prediction; Sustainable water management; Awash River basin.
ACKNOWLEDGMENTS

I would like to acknowledge all organizations and people who have supported me in one way or another to produce this thesis. The research was supported by the Swedish International Development Cooperation Agency (SIDA), Department for Research Cooperation and StandUp for Energy.

First, I would like to express my sincere respect to my former supervisor Bijan Dargahi for giving me the opportunity to start my research work and for introducing me to his invaluable expertise. My thanks also go to Anders Wörman for his advice and all the staff in the division of Hydraulic Engineering, for all the support and the interesting chats in the little ‘fika’ room. I would then like to express my utmost thanks and gratitude to my main supervisor Berit Balfors for her kindness and critical thinking, my co-supervisor Ulla Mörtberg for all the support and her encouragement to make me think out of the box. I would like to extend my gratitude and thanks to my co-supervisor Shimelis Setegn for providing me data and the useful comments on the manuscripts. Further, my special thanks go to Muluneh Mekonnen, Visiting Scientist at National Hydrology Research Institute, Environment Canada, for his comments on the manuscripts and his continuous support in every way he can.

I am very grateful to Britt Chow and Aira Saarelainen for all their heartfelt concerns to make me feel comfortable and their unconditional effort to keep me smile throughout my stay in KTH. Thank you Jerzy for all your kindness and effort to fix my never ending computer problems! I would like to extend my thanks to all colleagues at the department of LWR who have supported me with useful advice and also help me in practical issues. My special appreciation and thanks goes to those who have been participating in resolving the ups and downs occurred in my journey and giving me important tips, above all Joanne Fernlund. Your concern encouraged me to come this far.

Thank you my dear friends here and abroad for your support and encouragement to make this happen! My appreciation goes to my husband’s families for their support and the great times we spent together every time we get the opportunity. My special thanks go to Abune Elias for his spiritual and fatherly concerns; it feels like gaining back a lost father. My gratitude extends to my sister in-law Meseret Mengistu for her concern and support not to mention her vast knowledge and wisdom she shared with me. My genuine thanks go to my dearest mom, Ewuye, for her eternal love and for all her miseries in trying to provide the best of everything for her children. Thanks to my brothers for always being available when I needed to hear their voices and for all the humorous chat we had. I have no words to forward to my beloved husband, Misael for sharing the best and the worst part of life with me and for all he had to go through while I am away. I sincerely admire his amazing patience particularly to our ‘Terrible-Two’ little angel, Emanuel who is the great source of my deep joy.
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INTRODUCTION

Water is a major issue in life that needs to be protected and nourished. “Water is not a commercial product like any other but, rather, a heritage which must be protected, defended and treated as such”, as stated in the European Union Water Framework Directive (WFD, EU 2000). The growing pressure on the world’s fresh water resources is mainly due to and enforced by population growth that leads to conflicts between demands for different purposes. Water is increasingly seen as a resource for renewable energy generation, involving construction of dams and reservoirs for hydropower, to meet increasing energy demands for enabling development and economic growth. At the same time, water is used for other major welfare issues, such as irrigation for food security and for household supply. As a consequence, some of the common problems related to water faced by many countries are shortage, quality deterioration and flood impacts, which call for a greater awareness and action. One of the United Nations Millennium Development Goals (MDG) adopted by world leaders in the year 2000 is to halve the proportion of people without sustainable access to safe drinking water (UN, 2000).

However, unsustainable ways of constructing water infrastructure and utilizing water lead to considerable impacts, altering the regime of stream flows, flooding risk to the downstream and reducing or complete blocking of water to the ecosystem are among the many (see e.g. Molle et al., 2005). According to a study made on irrigation in Africa (Food and Agriculture Organization of the United Nations FAO, 2005), the main concern on water use is the conflict between the environment and agriculture particularly in lowland rural areas, where total base flows are diverted for irrigation without releasing water for ecological conservation. Further, excessive utilization of soil and forestry resources often results in negative impacts of water resources especially in the developing countries where extreme poverty forces those actions. Human activities induce pollution that further deteriorates the water resources, which threatens human health and the natural hydrologic scheme of aquatic ecosystems that add to the competition for water. The impact of its long term deterioration can be quantified in the form of social, economic and environmental aspects.

An appropriate way to handle the question of water is to use a single system of water management, which is built up by river basin, in an integrated way. As defined in the Global Water Partnership (GWP, 2000), ‘Integrated Water Resources Management (IWRM) is a process which promotes the co-ordinated 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.’ Hence, water resources management should be implemented in a sustainable way that encompasses balancing water needs, among other uses, for hydropower and irrigation, flood protection and providing environmental flows for biodiversity and ecosystem services.

Hydrological models are among the available tools used to forecast and predict the quantity and quality of water for decision makers (Chow et al., 1988). Some of these models could also predict the impacts of natural and anthropogenic changes on water resources and also to quantify the spatial and temporal availability of the resources. However, the challenges lie in choosing and utilizing these models for a specific basin and managerial plan.

Scope and objectives

The scope of this thesis is to understand and characterize the hydrological processes of a specific watershed using statistical and deterministic approaches as a contribution to the scarce information and database system for future management plans. The main objective of this study was to characterize the major hydrological components of the upper Awash River basin in Ethiopia under limited data conditions. It is believed that the research will contribute to fulfill the knowledge gap and to improve the baseline
information for planning sustainable water management, which aims balancing water demands for hydropower, irrigation and ecosystem services as well as flood risk. The specific objectives were: to investigate the applicability of a hydrological model in the study area for reliable characterization of hydrological processes of the catchment and further to assess and discuss the modeling uncertainties due to input data and other sources (Paper I), and to analyze the impacts of model structure with the main focus on assessment of the predictions from two different soil moisture accounting methods for specific sub-watersheds in the study area (Paper II).

**Organisation of the thesis**

The first section following this introduction presents the literature review starting with the global perspective and agreement for protection of water and the approaches to achieve a sustainable water resources management system. This section also includes a presentation of the theoretical background in the context of pros and cons of various types of hydrological models and a thorough description of the general background of the study area. The next section briefly describes the methods used to carry out the study and the detailed description of the modeling procedure. Then the results from and discussion of the different analyses and model applications are compiled in the following sections. Finally, conclusions from the analysis in relation to the overall problems and approaches end the thesis.

**WATER RESOURCES MANAGEMENT**

In this section some of the principles and challenges behind the water resources management, which includes the tools that could alleviate its implementation are presented.

**Integrated Water Resources Management (IWRM)**

IWRM is inspired by the principles from the Dublin statement on water and sustainable development made in the International Conference on Water and the Environment (ICWE) in Dublin, 1992. The first principle states that “fresh water is a finite and vulnerable resource, essential to sustain life, development and the environment” (ICWE, 1992). This principle demands a holistic approach to management, which identifies all the characteristics of the hydrological cycle and its interaction with other natural resources and ecosystems and considers the demands placed on the resource together with the threats to it.

The base for all IWRM is the hydrological cycle. Rain, the main component of the hydrological cycle, that falls on a watershed either intercepted by plants, immerse into the ground or runs over the surface (Chow, 1964). The water that runs overland and joins the stream at some point is the surface runoff while the water that infiltrates into the ground and makes its way into the stream much later is called base flow. How much infiltrates into the ground and how much runs over the surface depends on a number of different factor, including how porous the ground is, how wet the ground was already, how intense the rainfall is, how arid is the area, how much of the surface is covered by vegetation, how high is the slope in the area and how much of the area is impervious. This interrelationship calls for an integrated management between surface and groundwater.

Rivers are always moving and prone to change and both natural and human-induced mechanisms cause rivers to change continuously. Natural changes are gradual and possibly will balance in the long run, while the human-induced changes may magnify adverse effects and can imbalance the system rapidly. The degradation of the Mesopotamian marshlands in the Tigris and Euphrates river basins are examples of unsustainable damming and river channelization during the late 1980s (UNEP, 2001). Further, land use change brought by deforestation and urbanization alter rates of erosion, infiltration and overland flow. High rates of erosion are in turn responsible for reducing the capacity of reservoirs of dams constructed for hydropower and irrigation and induce flooding to the downstream (Flintan and Tamrat, 2002). Climate change
is also induced by land use change, which has impacts on both water quantity and quality (IPCC, 2000). The increment of rainfall intensity, that causes detachment of soils on degraded and bare land that increase sediment transport and non-point sources pollutants to the streams; high surface runoff that washes out wastes and garbage, especially in urban areas with poor drainage systems, to the streams; and the increasing carbon dioxide content in the air that affects the acidity of rain water are some of the examples. The interaction shows that the hydrologic cycle goes through various complicated processes using air, soil, vegetation, surface and groundwater as a media. Hence, the integration of land and water management is indispensable to account for all the interactions and in managing the relationships between quantity and quality and upstream and downstream water interests (GWP, 2000).

According to GWP (2000), implementation of IWRM would come to a possibility when helped by management instruments, which are tools that enable and help decision-makers to make coherent choices between different alternatives. Among the methods, water resources assessments and development of its knowledge base are necessary for effective water management. In order to evaluate the resource availability and quality against the demands, the assessment should address the occurrence in space and time of both surface and groundwater. Likewise, Irvine et al. (2005) stated that effective implementation of the WFD requires utilization of mathematical models, to provide a synthesis of complex natural processes and to identify the likely response within and among domains of natural and anthropogenic changes.

**Hydrological models**

A hydrological model is an approximation of the complex reality using a system concept. A system is a group of interacting or interdependent components forming a complex whole. The overall intent of the hydrologic system analysis is to study the system function and predict its output. The models treat the hydrological cycle as a system that comprises its different components as inputs like precipitation and outputs like runoff, using a set of equations that links the inputs and outputs (Chow et al., 1988).

The existing hydrological simulation models can be grouped according to the runoff generation process considered in each model. When comparing models, stochastic and deterministic models are often considered to be at the top level of the classification tree, in accordance to the way they treat the randomness of hydrologic phenomena (e.g. Chow et al., 1988). Stochastic models use local hydrometric data to predict flows. These models allow for some randomness that results in different outputs and are based on analysis of past events, commonly rainfall and river discharge (e.g. Ahmad et al., 2001; Tesfaye et al., 2006). Deterministic models generally produce a single output of runoff for a given rainfall under identical physical environments. Deterministic models can be classified as; lumped models, where a variable or parameter is assumed to have an average value for the whole catchment, and distributed models, where all variables and parameters have different values that account for the spatial variation in the catchment.

Deterministic models can be further classified as empirical, conceptual and physically-based models. Empirical models, which are usually lumped, are based on analyses of parallel input-output time series with no explicit account of physical processes. One of the recent methods in this category is an Artificial Neural Network (ANN) model that has the ability to recursively learn from the data, also called a data-driven model (e.g. Govindaraju and Rao, 2000; Antar et al., 2006). Conceptual models, which can be lumped or distributed, are generally composed of mathematical descriptions of the processes of catchment response. These models represent the catchment as integrated conceptual components but also incorporate some aspects of physical processes. Some examples of the conceptual models are the Stanford Watershed Model (SWM, see Crawford and Linsely, 1966),
HBV (Bergström and Forsman, 1973), TOPMODEL (Beven and Kirkby, 1979), the Identification of unit Hydrographs And Component flows from Rainfall, Evaporation and Streamflow data (IHACRES, Jakeman and Hornberger, 1993) and the Soil and Water Assessment Tool (SWAT, Arnold et al., 1998). In both empirical and conceptual approaches measured hydrological variables, usually stream flow data, are needed for calibration in order to develop and parameterize the model. Physically-based models are based solidly on an understanding of the physical processes using fundamental hydrodynamic laws. These models are fully distributed and use a finite difference or finite element grid system. Some of the distributed models currently in use are the Systeme Hydrologique European model (SHE, Abbott et al., 1986), the Institute of Hydrology Distributed Model (IHDM, Calver and Wood, 1995) and Water & Environmental Consultants – Catchment (WEC-C, Croton and Barry, 2001). The main driving force in using physically-based models is their applicability in ungauged catchments with the assumption that all the parameters needed for the model are measurable. Detailed descriptions about the types of models could be found in e.g. Becker and Serban (1990), Refsgaard (1996), Jones (1997), Beven (2001), and Mulligan and Wainwright (2004).

**Constraints in selecting hydrological model**

Even though the development of models is well advanced, choosing an appropriate modeling system for practical applications of integrated management is still a challenge. In addition to the purpose of the modeling and the types of the analysis to perform, one has to consider various factors in relation to the model structure that includes process description, numerical discretization, effective parameterization and computational efficiency in time and cost. Moreover, an extensive data requirement in relation to its availability is the main constraint in model application.

Stochastic models attempt to establish a linkage between several phenomena from historical data without internal description of the physical processes involved. One of the common uses of this type of model is for forecasting inflows into a reservoir system. The simulated result could then be used for estimating reservoir storage requirements and determining optimal operating polices for the use of available water (Salas, 1993). Data requirements for this type of models are relatively low as compared to the physically based models. However, there is a need of long historical data to simulate a reliable future natural river flows. The parameterization process might be taken as easier since the number of parameters to be estimated is relatively small. Still, computationally they might not be necessarily faster than corresponding deterministic models due to the difficulties of generating good random numbers with equal likelihood appearance and non-correlated values in a row (Mulligan and Wainwright, 2004). On the other hand, since the prediction does not encompass the interaction with the soil or land use processes it is not possible to do analysis on different scenarios of land and water resources management, which is useful to detect negative impacts from anthropogenic changes.

Deterministic models complexity varies according to their representation of the spatial variability of a catchment and their process description. Empirical models are comparable with the stochastic models with regard to process description (Refsgaard, 1996). Physical processes are not involved in the assessment of the mathematical equations behind this type of models but rather are based on analysis of simultaneous input and output time series. The common use of this type of model is a rainfall-runoff modeling for individual catchments. Moreover, they have also been in use in conceptual and physically-based models as a generator of some components, for instance unit hydrograph models used to represent the ground water system in conceptual models (e.g. Refsgaard, 1996; Minns and Babovic, 1996). The data requirements and computational
needs are usually low in comparison to conceptual and physically-based models. Generally, empirical models have high predictive power. However, their low explanatory depth makes them specific to the given conditions and hard to generalize for application on other catchments with similar physical characteristics (Mulligan and Wainwright, 2004).

Conceptual lumped models use semi-empirical equations with physical basis underneath to describe the hydrological processes, mainly due to their behavior of using the average value of parameters and variables for the whole catchment (Refsgaard, 1996). This type of models represents water flows in the catchment as individual storages corresponding to the different components that are interlinked in a row. Data requirements are low in comparison to the fully distributed models, which makes them suitable to use in most cases. This type of model has a number of parameters that should be calibrated using observed data for a specific application (Sorooshian, 1991). The computational efficiency could vary according to their complexity, for instance the number of free parameters to be calibrated. The common use of this type of model is for the simulation of rainfall-runoff process for flow forecasting. They also can give an indication of the effects of land use changes in qualitative and quantitative ways with a minimum amount of data (Merritt et al, 2003). So in the case of minimum requirements of detail description of the area, this type of model might be a good choice. However, their limited representation of the spatial variability of the natural system might restrict their applicability for integrated management purpose.

Physically-based distributed models calculate the flows of water and energy directly from the fundamental physical equations with the law of conservation as a foundation. This type of model represents the spatial variability of nature by splitting the catchment into either square cells or triangular irregular networks. Apart from the detailed description of the hydrological processes, the models provide potentially more truthful explanations of the catchment in comparison to the other models (Refsgaard, 1996). The common use of this type of model is for prediction of the effects of natural and anthropogenic changes in the catchments on stream flow, for instance surface and ground water development for hydropower or irrigation. However, the major constraint is the extensive data requirements, since all parameters that correspond to each modeling unit are assumed to be measurable from the field. Practically, it is impossible to measure such amount of data for different reasons, for instance the time and cost of measurement and the inadequacy of the available measurement techniques. These models tend to have good explanatory depth but low predictive power (Mulligan and Wainwright, 2004). Hence, the models often need to be calibrated to get good agreement with observed data. Moreover, the availability of computational efficient machine to run these models is another constraint to consider.

Semi-distributed models use multiple lumped units in a catchment either as subbasins or hydrological response units (HRU), with a perception that the response of the grouped cells ought to be similar. Their hydrological process description is based on the conceptual type. This type of model can compromise between the distributed and lumped models in their representation of spatial variability and data requirement (Merritt et al, 2003). In addition, these models can offer computational and parametric efficiency in the case of integrated modeling of the units (Irvine et al., 2005).

Challenges in the study area

Ethiopia is one of the countries that can be considered to have abundant water resources, available for hydropower and irrigation, at the same time as having significant problems related to water resources, such as flooding, drought and depletion of ecosystem services. Despite the fact of the substantial hydropower potential, it has one of the lowest levels of per capita electrical consumption in the world (Flintan and Tamrat, 2002). The country plans for major
investments in dams for hydropower purposes, which at the same time are expected to provide water for irrigation and flood control (Ministry of Water and Energy, 2010). On the other hand, the country still needs to work hard to fulfill the MDG that focuses on sustainable access to safe drinking water. According to the MDG reports (2010), currently the country lies on less than 50% coverage based on the indicator that stands for proportion of population using an improved drinking water source.

The Awash River basin is one of the significant spots, from development aspect, from the total of eight basins in the country. The basin is located in the Rift Valley (Figure 1) and is at a leading position in the development practice of the country, particularly in irrigation. The Awash River originates at an elevation of about 3000 m a.s.l. in the central part of Ethiopia and joins Lake Abe at an elevation of about 250 m a.s.l. after flowing for a total of 1200 km. The basin covers a total area of about 113,000 km² and drains in six regional states that include the capital city, Addis Abeba. The population of the basin is estimated to be around 14 million as derived from the 1994 population and housing census (Ministry of Water and Energy, 2010). According to Taddese et al. (2003), there are three functional dams in the basin for hydropower generation and irrigation development. Furthermore, the majority (48 to 70%) of the existing large-scale irrigated agriculture of the country is located along this river (Flintan and Tamrat, 2002; Achamyeleh, 2003).

The major problems that restraints the development in the Awash River basin are a recurrent large scale flooding and drought. The impacts of flooding so far include both the tragic human life’s loss and extensive property damages (Emergency appeal, 2006). According to Desalegn (2006), the occurrence of drought is, on average, once every two years and causes a great deal of damage to crops and livestock. Water management problems and investments in inappropriate development projects hinder the prevention and mitigation of the impacts. The major causes of the disasters include population growth, wetland degradation, soil erosion

Figure 1. Location map of the study area.
and sedimentation. The impacts from the population growth result in deforestation and overgrazing that in turn increase the soil erosion in the basin. The severe and uninhibited soil erosion results in the siltation of the major reservoirs. Koka dam is one of the important reservoirs affected by the sedimentation. It has been in use starting from 1960 for hydropower generation, irrigation developments in the downstream and also as flood attenuation during the heavy rain seasons. According to Achamyeleh (2003), the designers of the dam underestimated the severity of sedimentation on the life of the reservoir. The reduction in the storage capacity emphasizes spillage requirements in flood situations and worsening water shortages during dry periods (Piguet, 2001). Wetlands are being converted to agricultural lands and reservoirs that result in degradation and destruction of the natural ecosystems of the basin (Flintan and Tamrat, 2002). In addition, the neglected role of the wetlands in providing dry season grazing and the constructions that prevent the flooding of the grazing lands creates conflicts among the pastoralists (Flintan and Tamrat, 2002; Taddese et al., 2003). Moreover, water shortage and displacement from the grazing lands adds to the conflicts among different ethnic pastoralists and also with the large-scale irrigation organizations and commercial farmers (Piguet, 2001, 2002). These further result in tampering and destroying of constructions of dykes and drainages to induce flooding to the dry grazing lands (Achamyeleh, 2003).

The water quality deterioration is another important factor that stresses the shortage of water in this basin. The water quality issue in the river and its tributaries that includes lake Koka has been discussed by many (e.g. Alemayehu, 2001; Zinabu and Pearce, 2003; Kebbede, 2004; Prabu, 2009). The studies so far agreed that the most probable sources of the pollutants are untreated effluents from factories and industries in the surrounding cities and also direct discharge of domestic wastes (both solid and sewage water). Among the identified pollutants, with high risk for human and animal health, heavy metals (like As, Cr, Fe, Mn and Se), nitrate, phosphate, E.coli, and coliform are the common ones.

Hence, these challenges need integrated water resources management that could alleviate addressing of the specific demands from each stakeholder. The looking for the optimum solution should basically start with proper characterizing of the basin with the help of the available and appropriate tools like hydrological models.

**METHODS**

In this section the methods used to conduct the research are described briefly. Further description is presented in the appended papers.

**Literature review**

A literature review was conducted on IWRM and different types of hydrological models. The main emphasis was given to present the various aspects of the models in utilizing them as tools to implement IWRM and also the constraints in selecting a particular model for a specific location.

**Statistical analysis**

The application of standard statistical tools for the analyses of the available hydro-meteorological data was one of the approaches used in this study. The analysis was made to get an insight of the correlation between the available climate and stream flow measurements at the headwaters of the Awash River basin. The spatial distribution and representativeness of rainfall data in relation to observed stream flow data was assessed using a correlation coefficient method. The analysis was based on the daily data from the available rainfall gauges and stream flow measurements used in the study. Additional data sets of daily precipitation was calculated, based on area weighed principle, for some of the sub-watersheds that contains more than one sub-basin. The reason for the use of these additional data-sets was to relate the analysis with the simulated results from the model application. Since the model used the values from the nearest station for each sub-basin, in the case of a watershed composed of two or
more sub-basins the value would be area-weighted. In addition, the annual flow duration curve was also analyzed at the outlet to characterize the ability of the watershed to provide flows of various magnitudes. The shape of a flow duration curve is also helpful in evaluating the stream and watershed characteristics depending on the time scale used in preparing the curve.

**Hydrological modeling**

Characterization of the specified watershed was continued by adapting a hydrological model under limited data conditions. The application of the model involved model setup, sensitivity analysis, calibration, and uncertainty analysis. The performance of the model was evaluated by comparing the simulated flow hydrograph with the observed hydrograph visually and also using three model goodness-of-fit statistics methods. The modeling protocol, as proposed in Anderson and Woessner (1992) and later modified in Refsgaard (1996), was adapted for this study. A detailed description of the modeling process follows in the coming section.

**Modeling Protocol**

The procedure in the protocol (Figure 2) starts by clearly defining the purpose of the application or the modeling effort. As previously mentioned, the goal of this study is to characterize different components of the hydrological processes and to set up a model for future use of assessment of the effects from different management plans on stream flows. This step will help to identify which type of modeling system is suitable to solve or get an insight to the defined problem.

The second step is to build the conceptual model of the system based on the specific purpose. Identification of the system boundaries, available data collection from the representative authorities and literature reviews in addition to the field visits of the study area are all in this category. In addition to the defined purpose, the complexity of the model to be chosen depends on the analysis of the available data. The available data collected for this study includes; digital elevation models (DEM) with 30 m posting interval were downloaded from the official website of Earth Remote Sensing Data Analysis Center of Japan (ERSDAC, 2009), climate data (daily rainfall and temperature) from National Meteorological Agency of Ethiopia, stream flow measurements of five gauging stations from Ministry of Water and Energy of Ethiopia, land use and soil maps including their physical and chemical properties for parameter assigning (Chekol, 2006) and previous studies for comparison. This step helps to identify the outlet of the watershed to be analyzed (that would determine the system boundaries) and gives emphasis on the available parameters including their measurement scale (that would determine the appropriate numerical discretization). Based on the availability of the data, the present study focuses on the uppermost part of the Awash River basin, which is located between latitude 9° 18' N and 8° 17' N and longitude 37° 57' E and 39° 4' E. The area coverage of the watershed is about 7630 km² with an outlet at the Hombole gauging station. Some of the main streams that construct the Upper Awash River Basin are the Holeta, Berga, Akaki and Melka Kuntire streams. Table 1 summarizes the characteristics of the sub-watersheds.

Model selection is where the mathematical model will be either selected from the existing codes or modified by adding components to an existing one or developed from scratch. Since the scope of this study was to apply the models for the specified purpose the model selection was made from the existing hydrological models that have been successfully verified by others in different places. The selection was then based on the combined analysis of the previous steps and the accessibility of the models from the cost and user friendliness aspects. For this study the semi-distributed model known as Soil and Water Assessment Tool (SWAT) was selected.
SWAT is developed to examine the influence of topographic, land use, soil and climatic conditions on stream flow and sediment yield. It has also been used to predict the potential for hydropower (e.g. Kusre et al., 2010) as well as the impact of land management practices on water, sediment and agricultural chemical yields (Neitsch et al., 2005). It is a freely available model that can be utilized either from the source code or from the Geographic Information System (GIS) interfaces, which simplifies the integration of various spatial environmental data and the use of bulk data. It is a continuous time model and allows for a simulation of different physical processes in a watershed. The spatial unit for rainfall-runoff calculations is the Hydrologic Response Unit (HRU), which is a lumped land area within a sub-watershed comprised of unique land cover, soil, slope, and management combinations. The hydrological components (like surface flow, lateral flow, groundwater flow and evapotranspiration) are calculated for each HRU through the water balance. The cumulative total over a sub-watershed then gives the hydrological balance and main stream flow for that sub-watershed. The overall watershed hydrologic balance including stream flow at the outlet of the whole watershed is then calculated from the contribution of the upstream sub-watersheds. The hydrology part of the model is separated into two: the land phase and the routing phase of the hydrologic cycle.
The land phase of the hydrologic cycle controls the amount of water that goes to the main channel from each sub-watershed while the routing phase controls the movement of water through the channel network of the watershed to the outlet.

In this study, the calculation of surface runoff was made using the modified Soil Conservation Service (SCS) curve number procedure (USDA-SCS, 1972). This method uses two equations for runoff, of which the first one relates runoff to rainfall and retention parameter while the second equation relates the retention parameter to the curve number (Paper II). The retention parameter is the maximum potential difference between rainfall and runoff starting at the time the storm begins and used in the daily curve number calculation. The model incorporates two different options for calculating the retention parameter. The initial and default setup is to allow the retention parameter to vary with soil profile water content (here after called SM), which is characterized by the field capacity, the wilting point and the saturation water content. The second method is to allow it to vary with the accumulated plant evapotranspiration (here after called PT), which minimizes the impact of depending on soil storage and gives emphasis on antecedent climate.

For the calculation of evapotranspiration, Hargreaves method (Hargreaves et al., 1985) that only needs air temperature data was used. Since the curve number method is used to calculate the surface runoff, the amount of water that infiltrates to the soil profile is calculated as the difference between the amount of rainfall and the amount of surface runoff. The rate and velocity of flow is defined by Manning’s equation. Two variations of the kinematic wave model are incorporated in SWAT to route the water through the channel network; variable storage is the primary method and Muskingum River routing is the other option. Detailed description of the model could be found in Neitsch et al. (2005).

Model construction is the setup of the collected data to a platform where the modeling task takes place. In this study, the setup started with the delineation of the watershed from the DEM with the help of the GIS interface. This was followed by the definition of the stream network, setting of the different sub-basins outlets that correspond to the stream flow data and discretization of the watershed into HRU’s based on the land use, soil and slope data. This step also involved setting the initial conditions (like antecedent soil moisture content) and preliminary selection of parameter values from the input data.

Performance criteria should be established in order to evaluate the model output in comparison to the observed data during the calibration and validation process. The criteria should encompass the desired accuracy for the specific purpose in accordance with the realistic condition of the input data. In this study, the performance of the model was evaluated by comparing the simulated stream flow hydrograph with the observed hydrograph visually and also using three model goodness-of-fit measures;

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Holeta</th>
<th>Berga</th>
<th>Akaki</th>
<th>Melka Kuntire</th>
<th>Hombole</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size (km²)</td>
<td>131.1</td>
<td>216.8</td>
<td>884.3</td>
<td>4501.0</td>
<td>7626.3</td>
</tr>
<tr>
<td>Dominant slope (%) / Areal coverage (%)</td>
<td>&gt;15/ 42.6</td>
<td>&gt;15/ 36.5</td>
<td>8-15/33.4</td>
<td>2.5 / 30.8</td>
<td>2.5/ 28.9</td>
</tr>
<tr>
<td>Average elevation (m a.s.l.)</td>
<td>2544</td>
<td>2652</td>
<td>2371</td>
<td>2048</td>
<td>2018</td>
</tr>
<tr>
<td>Dominant soil type / depth (mm)</td>
<td>Luvisols / 1800</td>
<td>Luvisols / 1800</td>
<td>Vertisols / 2422</td>
<td>Vertisols / 2422</td>
<td>Vertisols / 2422</td>
</tr>
<tr>
<td>Dominant land use</td>
<td>Corn</td>
<td>Durum Wheat</td>
<td>Durum Wheat</td>
<td>Eragrostis Teff</td>
<td>Eragrostis Teff</td>
</tr>
</tbody>
</table>
Nash-Sutcliff Efficiency (NSE), coefficient of determination ($R^2$) and percent bias (PBIAS), which are widely used in hydrology (Moriasi et al., 2007). The performance of the model can be explained based on the recommended ranges: NSE values greater than 0.75 are considered to show good model efficiency, NSE between 0.36 and 0.75 shows satisfactory performance and values less than 0.36 are considered to be unsatisfactory (e.g. Motovilov et al., 1999; Moriasi et al., 2007; Van Liew et al., 2007). Similarly, PBIAS values greater than and equal to twenty five percent ($\pm 25\%$) are considered satisfactory.

**Sensitivity analysis** is the step where the uncertainties of the modeling process, either due to model structure or the estimated parameter values, could be evaluated. It also helps to prioritize parameters to include in the calibration process, particularly for models with considerable amount of parameters. In this study, the sensitivity analysis was performed to select the most sensitive parameters, out of the total of 27 flow parameters that are included in SWAT, for calibration. A sensitive parameter, in this study, was one that changed the model outputs of the stream flow significantly per unit change in its value. For this purpose, the automated Latin Hypercube One-factor-At-a-Time (LH-OAT, van Griensven et al. 2006) global sensitivity analysis procedure was used. The structure of the model was adjusted interactively to evaluate the different methods (one at a time) that were incorporated in the model, which concerned the estimation of retention parameters (SM and PT) and channel routing (variable storage and Muskingum). The analysis was based on the model performance on simulating a realistic stream flow that best represented the observed value.

**Calibration** is the process of finding the optimum set of parameters that would help the model to reproduce the observed data within the desired accuracy. The calibration of the selected sensitive parameters was undertaken in different steps. In Paper I, manual calibration (trial-and-error) was the first step to reach at some level of agreement with the observed stream flow and also to minimize the potential range that bound the value of each parameter. Then the automatic calibration and uncertainty analysis method, Parameter Solution (ParaSol, van Griensven and Meixner, 2007), which is incorporated in SWAT, was used. The Objective Function (OF) used in this study was the Sum of the Squares of the residuals (SSQ) with an objective of minimizing the differences between the simulated and measured time series. Since SSQ has a high priority of minimizing the large differences and often tend to force the model to underestimate the peak flows for a result of lower OF values (e.g. Eckhardt and Arnold, 2001), further tuning of parameters was made manually by visual comparison of the simulated and observed hydrographs. In Paper II, the manual calibration was done only for the two most sensitive parameters, selected based on the previous experience (Paper I), and all the parameter space was used. The calibration was based on the first three years of data (1996-1998).

**Validation** is the step where the capabilities of the calibrated model in simulating acceptable results could be confirmed. In this study, the validation of the model was performed to test if the calibrated parameter set would behave consistently for the watershed using different observed datasets in another period than the calibration (1999-2000). In this case, the stream flow dataset was the only observed data used for model validation. In Paper I, the performance of the model was also evaluated based on the stream flow prediction at four interior points from a parent watershed calibration. The other three interior points at tributary rivers, Holeta, Berga and Melka Kuntire were used to evaluate the model performance based on the parent watershed (Hombole) calibration, in a similar way as discussed in Reed et al. (2004). In order to comprehend the ability of the model in simulating for un-gauged watersheds the discharge data from the interior points were not used for the calibration process, but left for validation. In the case of Akaki sub-watershed, the study evaluated two scenarios; the calibrated result from
using its own discharge data and as a validation for Hombole calibration.

**Prediction** is the step where the response of the watershed to future changes would be quantified by applying the calibrated model. The calibrated parameter values and the catchment conditions would be kept unchanged while checking the effects of different scenarios or estimated changes in the watershed. The uncertainty at this step includes both the uncertainties from the calibrated parameters and from the estimated future spatial and temporal changes. Since the scope of the current study is to setup the modeling system for a specific watershed, this step was forwarded to the future task, which is to assess the impacts of land use and water resources management plans in the study area.

**Presentation of results** could be done in different ways, like reports, graphs or even animations. A clear presentation of the findings is essential for a good understanding of the problems and for reaching consensus between different stakeholders as well as to help decision makers. The results of this study are compiled in the following chapter.

**Postaudit** is another way of validation of the model prediction for a specific watershed. This step should be performed a number of years after the modeling task, which would allow adequate time for significant changes to occur. The validation would then be based on the comparison between the predicted values and the collected new data for the corresponding period. In the case of unsatisfactory outcomes, this step will help to redesign the model through changes in the conceptual model or in the parameter values.

**RESULTS AND DISCUSSION**

Summaries of the results and discussion from the two approaches, statistical and modeling, are presented in this section. The results are compiled in separate sub-sections.

**Results from the statistical analysis**

The analysis on the hydro-meteorological data was based on the available temperature, precipitation and streamflow measurements (Paper I). The following two sub-sections briefly describe the outcome.

**Hydro-meteorological time series trend analysis**

**Air temperature** was analyzed based on the available ten years (1996-2006) data from two stations (Addis Abeba Observation and Debre Zeit). The months with the maximum and minimum average temperature occurrences were May and December respectively, for both stations. However, the variation between different months was not significant as is indicated by the rather low values of the standard deviation (on average 1.1). The altitude difference, which is 2408 m for Addis Abeba Observation and 1900 m for Debre Zeit, could explain their slight distinction in temperature between the corresponding months of the two stations (on average Debre Zeit is warmer by 2.2 °C throughout the year).

The **precipitation** data was analyzed from the available eight stations in the watershed. The length of the recordings varied between stations, with the maximum being 45 years (1961-2006). However, the majority lied between the years 1982 and 2002 with a 20 year length of record. The analysis showed that the pattern and character of rainfall varied in different parts of the country mainly due to its geographic location and topography (Degefu, 1987; Bekele, 1997). Out of the analyzed eight stations, three of them (Addisalem, Ginchi and Tulubolo) falls in the regime characterized by a mono-modal rainfall pattern from March to September. The rest of the stations fall in the regime characterized by three distinct seasons; wet, small rain and dry seasons. The wet season starts in June and runs up to September. The small rain season runs from February to May while the dry season usually occurs from October to January. The standard deviation of the rainfall data for each month was calculated based on all stations and it showed that the variation between the stations was high during the wet season (37 mm in August) and low in dry season (3.8 mm in December). The calculated area weighed rainfall for Hombole watershed adapted the mono-modal pattern after the first three
sustained water resources management: case study of the Awash River Basin stations. Still, the amount of rainfall showed
a distinct boundary between the two rain
seasons (wet and small rain) while the sepa-
rator, the relatively short ‘dry’ period as de-
scribed in Bekele (1997), in between (in this
case during May) overturned and resulted in
a single peak rainfall pattern.

The flow regimes of the Hombole watershed
was analyzed using 39 years of observed stream flow data (1968 - 2006). The average
annual depth of runoff in the watershed was
estimated at 177 mm. The wettest year was
1971 with a 313 mm discharge and the
driest, with 86 mm discharge, was the year
1987. The coefficient of variation on annual
basis is about 0.29 and the flow regime is
characterized by elongated periods of med-
ium to high flow and shorter intermingled
periods of low flow. The frequency analysis
showed that the exceedance probability
from the mean annual value was 43%, from
which 23% exceeds the mean by 10%
(Figure 3). The shape of the daily duration
curve, which was flat towards its tail, sug-
gests for a potential of good storage capacity
in the watershed. The average monthly flow
pursued the rainfall trend which is a
mono-modal curve with a peak in August
(Figure 4).

Spatial distribution and representativeness of
rainfall data
One of the major limitations to large area
hydrologic modeling is the spatial variability
associated with precipitation. Even though
eight rainfall gages were used in this study,
the spatial distribution in relation to the
watershed area could be considered to be
inadequate. According to Arnold et al.
(1998), using one gage to represent an entire sub-watershed or even by means of area weighed methods for rainfall representation can cause considerable error in runoff estimation. However, the correlation coefficient of the precipitation data and observed stream flow might help in explaining the model performance in different sub-watersheds. According to the analysis, the correlation between the observed stream flow at the Akaki sub-watershed and the corresponding rainfall gage considered by SWAT (in this case area weighed) was poor in relation to both Melka Kuntire and Hombole watersheds (Table 2). Holeta and Berga sub-watersheds, both were having only a single rainfall station had the lowest correlation coefficients relative to the others.

### Results from hydrological modeling

The model application starts with the sensitivity analysis, both on model structure and flow parameters. This section presents the analysis from both papers (Paper I and Paper II) in separate sub-sections according to the different procedures.

#### Sensitivity analysis on model structure

In Paper II, the analysis of the model structure was based on the different combinations of methods for estimation of retention parameter and channel routing. Initially, the un-calibrated simulation results from the different combinations were compared statistically and visually using hydrographs. The default setup of the model used; SM for the retention parameter calculation and the variable storage routing method. The hydrograph produced by this combination was dominated by high runoff events during the dry and small rainy season while relatively low flow during the main rain season when compared to the observed hydrograph (Figure 5). The comparison on daily basis indicated that the changing of the retention parameter calculation method to PT improved the fit of the predicted vs. observed daily stream flow significantly for some of the sub-watersheds. The significant change was on the falling limb and the base flow recession (Figure 5). The change in the channel routing method to Muskingum improved the results in all sub-watersheds in combination with both SM and PT methods. This method helped to minimize the overestimation of peak flows in some cases. The summary from the model performance evaluators (Table 3) show that the different measures favored different combinations, which could be considered as an indication for further analysis prior any conclusion. However, the majority of values still show that Muskingum is giving a better performance for this specific study.

One common reaction that was observed in Holeta and Berga sub-watersheds was that the catchments seemed to respond only to the surface runoff that came from the heavy rain during the wet season. The simulation underestimated the fraction of water contri-

<table>
<thead>
<tr>
<th>Rainfall stations</th>
<th>Holeta Q</th>
<th>Berga Q</th>
<th>Akaki Q</th>
<th>Melka Kuntire Q</th>
<th>Hombole Q</th>
</tr>
</thead>
<tbody>
<tr>
<td>Addis Abeba Bole</td>
<td>0.22</td>
<td>0.28</td>
<td>0.30</td>
<td>0.32</td>
<td>0.31</td>
</tr>
<tr>
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<tr>
<td>Addisalem</td>
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<td>0.33</td>
<td>0.33</td>
<td>0.30</td>
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<tr>
<td>Debre Zeit</td>
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<td>0.25</td>
<td>0.27</td>
<td>0.33</td>
<td>0.36</td>
</tr>
<tr>
<td>Ginchi</td>
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<td>0.24</td>
<td>0.20</td>
<td>0.29</td>
<td>0.27</td>
</tr>
<tr>
<td>Tulubolo</td>
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<td>0.29</td>
<td>0.27</td>
<td>0.41</td>
<td>0.40</td>
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<td>0.16</td>
<td>0.21</td>
<td>0.25</td>
<td>0.25</td>
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<td>Akaki area weighted</td>
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<td>0.40</td>
<td>0.39</td>
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<tr>
<td>Melka Kuntire area weighted</td>
<td>0.32</td>
<td>0.37</td>
<td>0.33</td>
<td>0.52</td>
<td>0.49</td>
</tr>
<tr>
<td>Hombolee area weighted</td>
<td>0.36</td>
<td>0.41</td>
<td>0.41</td>
<td>0.56</td>
<td>0.54</td>
</tr>
</tbody>
</table>
Hydrological modeling as a tool for sustainable water resources management: case study of the Awash River Basin

Figure 5. Hydrographs that compare observed and simulated stream flows using the Muskingum method combined with the SM method (top) and PT method (bottom) at Akaki sub-watershed for the year 1996.

buted by the base flow during that time. The hydrographs showed poor base flow recession time in comparison to the observed flow. This could be the combined result of their commonly being the steepest and dominated by relatively shallow soils in comparison to the others.

Sensitivity analysis of parameters
In both papers the sensitivity analysis indicated that the stream flow prediction was sensitive to variation in surface water, ground water and soil parameters. Among the twenty seven hydrological parameters, the identified most sensitive ones were the base flow alpha factor (ALPHA_BF), initial SCS curve number II (CN2), soil evaporation compensation factor (ESCO), ground water delay (GW_DELAY), deep aquifer percolation fraction (RCHRG_DP), available soil water capacity (SOL_AWC), saturated hydraulic conductivity (SOL_K), and surface runoff lag time (SURLAG).

In Paper II the sensitivity of the different hydrological components were analyzed based on the weighting coefficient (cncoef) within the parameter’s possible range of values. This single parameter is associated with the PT method, which is used to calculate the retention parameter for daily curve number calculations. The sensitivity analysis of the cncoef was performed manually and showed that the weighting coefficient and surface runoff were directly proportional while the relation with subsurface runoff was inversely proportional. This result is similar to the study discussed by Kannan et al. (2008). The default value for cncoef was 1 with the possible range between 0 and 2. The increasing of the parameter value also increased the mean of the total flow with an average proportion of about 2.5 mm for each 0.1 increment. The base flow fraction accounting problem, which was discussed in the sensitivity of the model structure, for the two smaller sub-watersheds was also tested. The result shows the improvement achieved
by changing \textit{cncoef} to 0.25 for Holeta sub-
 watershed in comparison to the default value and observed flow (Figure 6). The calibrated
 optimal values, based on the comparison of the base flow fraction between the observed and simulated flow, were 1.05 and 0.6 for Akaki and Hombole, respectively.

\textbf{Model calibration and validation}

The different calibration schemes, from both papers, produced slightly different hydrographs in both Akaki and Hombole watersheds. The simulated flow from Paper I showed a relatively better prediction of some peak flows (Figure 7). This was due to the final manual adjustment of some of the parameters, after performing the auto-

<table>
<thead>
<tr>
<th>Watershed</th>
<th>Method</th>
<th>NSE</th>
<th>R²</th>
<th>PBIAS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Holeta</td>
<td>SM - Variable Storage</td>
<td>-0.24</td>
<td>0.13</td>
<td>37.6</td>
</tr>
<tr>
<td></td>
<td>SM - Muskingum</td>
<td>-0.23</td>
<td>0.13</td>
<td>37.6</td>
</tr>
<tr>
<td></td>
<td>PT - Variable Storage</td>
<td>-2.26</td>
<td>0.06</td>
<td>49.93</td>
</tr>
<tr>
<td></td>
<td>PT - Muskingum</td>
<td>-2.16</td>
<td>0.06</td>
<td>49.94</td>
</tr>
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<td>Berga</td>
<td>SM - Variable Storage</td>
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<td>0.14</td>
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<td></td>
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<td>0.16</td>
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<tr>
<td></td>
<td>PT - Variable Storage</td>
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<td>0.12</td>
<td>9.45</td>
</tr>
<tr>
<td></td>
<td>PT - Muskingum</td>
<td>-0.48</td>
<td>0.13</td>
<td>9.46</td>
</tr>
<tr>
<td>Akaki</td>
<td>SM - Variable Storage</td>
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<td>9.05</td>
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<td>0.29</td>
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<tr>
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<td>10.43</td>
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<td>Melka Kuntire</td>
<td>SM - Variable Storage</td>
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<td>114.5</td>
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</tr>
<tr>
<td>Hombole</td>
<td>SM - Variable Storage</td>
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<td>0.43</td>
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<tr>
<td></td>
<td>SM - Muskingum</td>
<td>-0.33</td>
<td>0.52</td>
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<tr>
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<td></td>
<td>PT - Muskingum</td>
<td>-1.16</td>
<td>0.65</td>
<td>117.3</td>
</tr>
</tbody>
</table>
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The calibrated model was verified by the values from the performance evaluators (Table 4). The comparison with the simulated results from the uncalibrated model (default parameters) confirmed that the calibration was essential for this area. According to the evaluators, the relatively best performance in all the cases corresponded to the PT simulation from Paper II. On a daily basis, the NSE for Akaki and Hombole watersheds ranged, respectively, between 0.49 to 0.53 and 0.72 to 0.83. Similarly, the $R^2$ value ranged between 0.50 to 0.53 and 0.75 to 0.83 while the PBIAS ranged

![Figure 6. Hydrograph plots comparing the observed with two simulated stream flows using different weighting coefficient (cncoef) values in Holeta sub-watershed during the calibration period (1996-1998).](image)

![Figure 7. Daily observed hydrographs at Akaki (top) and Hombole (bottom) in comparison to the three different simulated flows during the calibration (1996-1998) and validation (1999-2000) periods.](image)
between (-8.9) to 0.3 and 12.0 to (-1.7). The negative and positive signs of the PBIAS indicate, respectively, the underestimation and overestimation of the total simulated flow in comparison to the observed flow. Based on the recommended ranges, the performance of the model lies on a satisfactory level for Akaki and good level for Hombole watershed.

On monthly basis the trend was similar to the daily time step. The NSE was 0.80 to 0.84 and 0.94 to 0.97 for Akaki and Hombole watersheds, respectively. Likewise, the $R^2$ value was 0.83 to 0.85 and 0.95 to 0.97 while the PBIAS was (-8.7) to 0.6 and 12.0 to (-1.6). According to the performance ranges, the model showed good performance in predicting the monthly discharges from both watersheds.

During the validation period (1999-2000), the analysis of the model performance showed that for the Akaki watershed, the underestimation of the observed total stream flow was in a much larger quantity than the calibration period. This might be explained by the contradiction in the trends of the annual mean rainfall and runoff for the year 1999. The mean annual runoff increased while the rainfall decreased in comparison to 1998 and vice versa when compared to 2000. For the Hombole watershed the maximum overestimation was observed in the year 2000 simulation result. The mean annual stream flow decreased gradually from 1998 whereas the average weighted rainfall for Hombole watershed increased from 1999 to 2000. This means that the observed total runoff for the year 2000 was relatively dry when compared to the observed annual rainfall. The overall performance, both during the calibration and the validation periods, might indicate that the model performed relatively well during wet years.

The difference between the two watersheds in model performance could be due to the forcing input data. The correlation between rainfall and runoff for Akaki watershed was poorer than for Hombole (Table 2). One of the main sources of model uncertainties is acknowledged (see e.g. Refsgaard and Storm, 1996; Beven, 2001) to be errors in the input variables such as rainfall and temperature. Hence, the poor model performance in the Akaki sub-watershed could be due to poor quality of the gauged climate variables as well as the very coarse spatial distribution of weather stations in the sub-watershed. Another possible reason is the aggregation of the discharges from the different upstream sub-watersheds to a larger area, in this case Hombole watershed, which might

| Table 4. Model performance statistics from the three different simulations for the prediction of stream flow in the Akaki and Hombole watersheds. ('Cal' stands for the calibration period, 1996-1998 and 'Val' stands for the validation period, 1999-2000, while PT(I) and PT(II) represents the simulation results from Paper I and II respectively using the PT method and SM represents the results from Paper II). |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Evaluator      | Akaki           | Hombole         |                 |                 |                 |                 |                 |
|                 | Observed Cal mean = 13.2 (m²/s) | Observed Cal mean = 52.9 (m²/s) |                 |                 |                 |                 |                 |
|                 | Observed Val mean = 12.9 (m²/s) | Observed Val mean = 39.9 (m²/s) |                 |                 |                 |                 |                 |
|                 | Daily           | Monthly         | Daily           | Monthly         | Daily           | Monthly         |                 |
|                 | PT(I)           | PT(II)          | SM              | PT(I)           | PT(II)          | SM              |                 |
| Mean (m³/s)    |                  |                 |                 |                  |                 |                 |                 |
| Cal            | 12.8            | 13.2            | 11.9            | 12.7            | 13.1            | 11.9            | 54.2            |
| Val            | 10.1            | 10.8            | 10.1            | 9.9             | 10.8            | 9.9             | 41.8            |
| NSE            |                  |                 |                 |                  |                 |                 |                 |
| Cal            | 0.53            | 0.53            | 0.49            | 0.82            | 0.84            | 0.80            | 0.72            |
| Val            | 0.55            | 0.44            | 0.50            | 0.82            | 0.75            | 0.77            | 0.71            |
| $R^2$          |                  |                 |                 |                  |                 |                 |                 |
| Cal            | 0.53            | 0.53            | 0.53            | 0.83            | 0.85            | 0.83            | 0.75            |
| Val            | 0.59            | 0.46            | 0.55            | 0.86            | 0.78            | 0.84            | 0.74            |
| PBIAS          |                  |                 |                 |                  |                 |                 |                 |
| Cal            | -2.9            | -0.3            | -8.9            | -2.6            | 0.6             | -8.7            | 2.3             |
| Val            | -23.4           | -17.4           | -23.1           | -23.3           | -17.1           | -22.9           | 3.6             |
|                 |                 |                 |                 |                  |                 |                 |                 |
Model validation at interior points

The model performance on interior points, based on a parent watershed calibration (Paper I), is summarized in Table 5. The sub-watersheds in the table are listed in order of increasing drainage area. A noticeable trend was an improvement in performance, on both the NSE and $R^2$ values, that was directly proportional with the size of the sub-watersheds. The performance was poor for the smaller interior points, in particular for Holeta and Berga. The possible explanation could be the insufficient capacity of smaller basins to dampen out input signals and consequent input errors as discussed in Reed et al. (2004) and Shrestha et al. (2005). The coefficient of variation for the daily stream flow data showed that the smaller sub-watersheds exhibited more variability than the larger ones, which could affect the accuracy of the simulation. According to Hirpa et al. (2010), the statistical analysis on daily flow data shows that the degree of multifractality of river flow decreases with increasing watershed area, which could point out the similarity between larger basins in preserving the different intensities of flow fluctuations. The study concludes that the watershed area is an important factor that controls the long memory of river flow fluctuations. Hence, the direct transferring of parameter values should be based on catchment characteristic analysis that consider the effects of the watershed area. On the other hand, the monthly variation showed that the catchments could, to some extent, stabilize the input signals at this time scale. The stream flow response seemed to incorporate the influence of the catchment characteristics and damp the fluctuations of the rainfall, which could explain the better performance of the model at a monthly time scale. The uncertainties that come from the spatial distribution of rainfall is also another possible reason as illustrated by the coefficients of the correlation analysis (Table 2).

The performance of the model at Akaki sub-watershed was analyzed from the two scenarios (Table 4 and Table 5); the first one was the performance based on the calibration of the model using the stream flow data of Akaki, and the second one was the performance of the model at Akaki as an interior point. The comparison, based on all the three model evaluators, showed that the model performed better in the first case (Table 4) for a daily time scale. The monthly time scale comparison indicated relatively poor performance in the first scenario during the calibration period while it showed better performance during the validation period. The PBIAS indicated a better performance in all years for the first scenario. Even though the performance of the model mostly got better by using the stream flow data for calibration, this result might also indicate the possibility of using the model for ungauged interior points having similar catchment characteristics with a gauged parent watershed.

<table>
<thead>
<tr>
<th>Evaluator</th>
<th>Period</th>
<th>Holeta</th>
<th>Berga</th>
<th>Akaki</th>
<th>Melka Kuntire</th>
</tr>
</thead>
<tbody>
<tr>
<td>NSE</td>
<td>Calibration</td>
<td>-1.00</td>
<td>-0.20</td>
<td>0.01</td>
<td>0.59</td>
</tr>
<tr>
<td></td>
<td>Validation</td>
<td>-0.38</td>
<td>0.29</td>
<td>-0.13</td>
<td>0.45</td>
</tr>
<tr>
<td>$R^2$</td>
<td>Calibration</td>
<td>0.10</td>
<td>0.39</td>
<td>0.21</td>
<td>0.64</td>
</tr>
<tr>
<td></td>
<td>Validation</td>
<td>0.05</td>
<td>0.37</td>
<td>0.08</td>
<td>0.38</td>
</tr>
<tr>
<td>PBIAS</td>
<td>Calibration</td>
<td>21.36</td>
<td>20.89</td>
<td>-8.87</td>
<td>-9.05</td>
</tr>
<tr>
<td></td>
<td>Validation</td>
<td>-17.46</td>
<td>-17.37</td>
<td>3.21</td>
<td>3.58</td>
</tr>
</tbody>
</table>
**Water balance of the upper Awash River Basin**

The main components of the upper Awash River basin simulated water budget were analyzed at the outlet of the watershed (Figure 8). The major component, as calculated from a 100% rainfall input, was evapotranspiration with an average 66% agreed in all the three simulations (two simulations with the PT method from the two different calibration schemes in Paper I and II and one simulation with the SM method in Paper II). The major difference between the two soil moisture accounting methods (PT and SM), for this specific watershed is on the accounting of surface runoff and base flow on annual basis. The PT method (Paper II) resulted in a 24 and 2% of surface runoff and base flow respectively. The SM method (Paper II) resulted in a 3.3 and 20.5% of surface runoff and base flow respectively. These results were compared with previous works, Moreda (1999) and Chekol (2006). According to Moreda (1999), using a 10-day and a monthly lumped conceptual rainfall-runoff model, the dominant flow is the inter flow (lateral flow) with 13% as compared to the base flow that accounts 2%. The study explained that due to the simulation time scale, the short intensive storms are likely smoothed (averaged) and surface runoff was not generated. On the other hand, the study by Chekol (2006), using the SM method in the SWAT model, indicates that the base flow is the important component with the amount of 9.8% from a 100% rainfall input while surface runoff is 6.8%. The comparison indicates that the SM method consistently simulated the base flow as a dominant contributor on annual basis (both in the current study and in Chekol (2006)), while the PT method is in accordance with the discussed results from Moreda (1999).

The analysis on annual basis (Paper I) for each simulated year showed that the loss of water through evapotranspiration was dominant in all years. The amount of evapotranspiration lost from the total annual precipitation reached at its maximum percentage in the driest year (1997). The foremost contributor to the water yield was the surface runoff with an exception of the year 1999 where the groundwater flow was greater, by about 1.2 mm. The soil water storage (including the vadose zone) was calculated as the difference between the input rainfall and the different output components.

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**Figure 8.** Water balance components of the Hombole watershed with the corresponding percentage from 100% precipitation input based on the three different simulations for the calibration period.
(Figure 8). The result indicates a gaining storage (positive) with a more pronounced gain in the relatively driest years (1997 and 1999) and an exception lose (negative) in the year 1996. The change in the soil water storage exhibited a strong correlation with the surface runoff regime. The increase in the amount of surface runoff was followed by a decrease in soil water storage. The trend of this relation was also similar with the other components. However, since the simulation was based only on the calibration of the streamflow, these results should further be validated with soil moisture measurements.

The sensitivity of the cncoef parameter was also checked on the calibrated model based on the annual water budget. The result indicated the possibilities of adjusting the surface runoff and groundwater flow components with a single parameter calibration. Changing the parameter to 0.5 from the calibrated 0.6 shifted some of the surface runoff contribution to the base flow while changing it to 0.7 resulted vice versa. Similar results have also been reported by Kannan et al. (2008).

**Model prediction performance and uncertainties**

The overall performance of the model depends on different factors. The forcing input data (like rainfall and temperature) and the observations used to calibrate and validate the model outputs (like the streamflow data) could be mentioned as the major uncertainty sources. Apart from data quality, in a place like the Awash River basin with an altitude range of 250 to 3600 m a.s.l., the extrapolation of rainfall from a distant gauge is an obvious source of bias. The possibilities of overcoming some of the drawbacks that concerns the quality and spatial distribution of input data by making use of radar rainfall data and remotely sensed soil moisture data has been documented (e.g. Jacobs et al., 2003; Moon et al., 2004; Jayakrishnan et al., 2005). Moreover, in this study, observed flow data was the only way of constraining the calibration and prediction process. Franks et al. (1998) suggested that in the case of availability of additional measured or realistic estimates of variables (in this case like soil moisture), a reduced uncertainty will be possible.

The main limitation in using a distributed model is the large number of parameters that needed to be optimized in order to reach an acceptable prediction of the output. Even though the parameters are measurable in the field, it is not practicable to get error-free measurements apart from the time and cost constraints. The scale of the measured parameters, that usually does not match the model element or discretization scale, which is much larger (Beven, 2001), also adds to the limitations. During the calibration process, the values of the parameters for best fit depend on the initial values, in this case the SWAT default parameter values designed for catchments in the United States. The optimal set of parameters might be different with improved objective function values with different initial conditions (Jones, 1997). The auto-calibration method used in this study gave only one optimum set of parameters. The existence of multiple optimal parameter sets that can give as good prediction of stream flow is usually possible, which is explained in the concept of equifinality of model structures and parameters (Beven, 1993; Beven, 2001; White and Chaubey, 2005). In this study, the Akaki sub-watershed used the potential parameter space (the SWAT default ranges) during the auto-calibration for all the free parameters. For Hombole two scenarios were tested: in Paper I a range were defined based on the manual calibration and in Paper II all the parameter space were used. This might explain the significant difference in the ALPHA_BF, REVAPMN and RCHRG_DP parameters between the two watersheds (Paper I) and also the differences in all the parameters between different simulations (Table 6).

Even though the SWAT model is semi-distributed based on HRU units, the parameterization in this study was done in a more lumped way, mainly on sub-basin scales, during the calibration process. The total number of HRUs was 399 and this large number made it difficult to calibrate
Table 6. The final estimate of, selected flow sensitive SWAT model parameters from the three different calibration procedures at Hombole station in accordance with their default value and calibration range. (PT (I) and PT (II) represents the calibration from Paper I and II respectively while SM from Paper II).

<table>
<thead>
<tr>
<th>Parameter Name</th>
<th>Default Value</th>
<th>Calibration Range</th>
<th>Final Estimate PT (II)</th>
<th>Calibration Range</th>
<th>Final Estimate</th>
<th>Calibration Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALPHA_BF</td>
<td>0.048</td>
<td>0-0.05</td>
<td>0.049</td>
<td>0-1</td>
<td>0.428</td>
<td>0.898</td>
</tr>
<tr>
<td>CN2</td>
<td>*</td>
<td>-20-0%</td>
<td>-17.5</td>
<td>±25%</td>
<td>3.1</td>
<td>-25</td>
</tr>
<tr>
<td>ESCO</td>
<td>0.95</td>
<td>0.5-0.95</td>
<td>0.65</td>
<td>0-1</td>
<td>0.04</td>
<td>0.01</td>
</tr>
<tr>
<td>GW_DELAY</td>
<td>31</td>
<td>0-10</td>
<td>0.305</td>
<td>0-1</td>
<td>0.49</td>
<td>0.05</td>
</tr>
<tr>
<td>RCHRG_DP</td>
<td>0.05</td>
<td>0.05-1</td>
<td>-10.3</td>
<td>±25%</td>
<td>16.03</td>
<td>24.9</td>
</tr>
<tr>
<td>SOL_AWC</td>
<td>**</td>
<td>-20-5%</td>
<td>-14</td>
<td>±25%</td>
<td>18.4</td>
<td>24.9</td>
</tr>
<tr>
<td>SOL_K</td>
<td>**</td>
<td>-20-5%</td>
<td>-10.3</td>
<td>±25%</td>
<td>16.03</td>
<td>-25</td>
</tr>
<tr>
<td>SURLAG</td>
<td>4</td>
<td>0-4</td>
<td>0.5</td>
<td>1-24</td>
<td>4.6</td>
<td>8.8</td>
</tr>
</tbody>
</table>

each of these separately. Apart from the spatial variation, the temporal variation is also important for areas characterized by a distinct seasonal trend. The calibration process for the curve number is especially sensitive for seasonal variation, in that the performance of the model would be improved at the expense of the peak flows and vice versa.

The SM method is reported to predict too much runoff in shallow soils and soils with low storage (e.g. Neitsch et al., 2005, Kannan et al. 2008). According to Kannan et al. (2008) the calibrated model using the PT method performs better than the SM method in the areas of low storage soils and shallow soils. The result of this study is also in accordance, which shows that the PT method improved the prediction of stream flow in the areas characterized by medium to low storage. The significant factor that was observed from the analysis was the capability of the methods in mimicking the seasonal variation of the rainfall and the retention capacity of the soils that in turn govern the surface runoff estimation. The quality of climate data and its representativeness to the catchment is vital since the core of this method was to depend more on antecedent climate conditions rather than on the soil storage. Further studies on similar watersheds would be necessary to validate the outcomes of this study and to help categorizing the characteristic of a catchment that could be modeled with good performance using the different methods.

Quantifying or predicting the different hydrological components is the initial step for sustainable water resources planning and management. Hence, it is important to understand the water balance and quantify the dominant components in a watershed before planning and implementation. In this study, the water balance investigation shows a disagreement between the two different methods on the estimation of the contribution from the base flow. Even though, the groundwater of this perennial river was expected to sustain in dry seasons (for instance not a single zero flow was recorded during the studied period), it is possible that the base flow could be recharged from other sources. Apart from local infiltration, springs and wetlands are among the potential sources. Moreover, faults and fractures could direct water from the neighboring watersheds. Hence, these calls for further study that accounts the influence of the geological formations and structural behavior of the watershed that could assist in quantifying the groundwater potential.

**Conclusions**

Distributed hydrological characterization of a catchment is one of the important information components to address the different questions in achieving a plan for sustainable water management. Adapting existing hydrological models, under limited data
conditions, is a feasible start to improve the reliability of stream flow prediction particularly in developing countries, where data is often scarce. Even though, the developments of hydrological models are well advanced, the challenge in making use of them is the substantial data requirements. Collecting more data could be the ultimate long term solution while making better use of available information. However, a substantial improvement is not always related with a bulk of data, rather with the relevancy of the data and systematized collection system. A complicating factor is though that the Awash River passes through six regional states, which could make it difficult to implement a basin wise integrated water resources management. For instance, the land management and development plans are convicted at regional scale or administrative boundaries. The hydro-meteorological data organization also follows this. Especially, the meteorological stations are grouped according to political regions, which make it difficult for researchers and practitioners to locate the representative stations in accordance with the corresponding basins. This may hinder the usability of the available data. Monitoring and evaluating of ongoing projects would also be possible with a proper water management system.

In the current study, an attempt was made to characterize the hydrological processes of the Awash River basin, in Ethiopia, using statistical and deterministic approaches as a contribution to fulfill the knowledge gap and the scarce information for future management plans. The study focuses on the assessment of the applicability of the SWAT model in the study area for reliable characterization of the catchment and the modeling uncertainties due to input data and model structure. The study could also be taken as a direction on where to focus from data collection and quality control aspects.

The model was successfully calibrated and validated at the outlet and at one interior point. The performance of the model was also evaluated at four interior river gauge stations. The comparison between the observed and simulated stream flow indicated that there was a good agreement between the observed and simulated discharge of the calibrated model, which was verified by higher values of coefficient of determination ($R^2$) and Nash-Sutcliff efficiency (NSE) and good agreement in the hydrographs. The model evaluation statistics for stream flows gave acceptable results that ranged from satisfactory to good, verified by NSE and $R^2 > 0.36$ and PBIAS ± 25%. Some of the relatively poor model performance could be due to poor quality of the gauged climate variables as well as the very coarse spatial distribution of weather stations in the sub-watersheds. Even though the model performed in a satisfactory level, the performance level should not be generalized equally for all purposes. The daily results are much more important than the monthly if the simulation is for flood analyses and flood protection or prevention plans. By contrast, for hydropower and irrigation purposes the monthly results could help for allocating and planning. Since the primary application of the SWAT model is for land management and agriculture, the calibrated model can be used to analyze the effects of change in land use and different management scenarios on stream flow regimes. The evaluation at the four interior points indicated that care must be taken on direct transferring of parameter values in association to watershed characteristics, with emphasis on drainage area.

Analysis was also made on the different options for estimating the retention parameter used in surface runoff generation with the Soil Conservation Service (SCS) curve number method. One depends on the soil water content (SM) and the other on antecedent climate (PT). While the predicted stream flow hydrographs showed an agreement between the two methods, the predicted annual water balance indicated a disagreement in quantifying the different hydrological components. The SM method estimated higher surface runoff contribution than the groundwater while the PT method estimated the other way around. Hence, further investigation is recommended that accounts the geological characteristics and
the sources of the base flow to make sure the occurrence of the groundwater in a sufficient amount for any future development. Overall, the present study indicates that proper care must be taken in selecting an appropriate tool for quantifying the different water balance components, which would be used for decision making, especially for un-gauged catchments where validation of model results is unattainable. Hence, a continuous research on quantifying and allocating water resources is indispensable for building information databases for decision makers. Thus, the management plan should be based on the availability of the resource, both temporally and spatially, in accordance with the basin characteristics.
REFERENCES


Hydrological modeling as a tool for sustainable water resources management: case study of the Awash River Basin


Other references

