UNIVERSITEIT GENT

FACULTY OF BIOSCIENCE ENGINEERING

Department of Forest and Water Management

WATER BALANCE MODELLING OF THE LAKE TANA AREA, ETHIOPIA

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Thesis submitted in fulfilment of the requirements for the degree of
Doctor (Ph.D.) of Applied Biological Sciences: Land and Water Management

Academic year 2014-2015

Water, like religion and ideology, has the power to move millions of people. Since the very birth of human civilization, people have moved to settle close to it. People move when there is too little of it. People move when there is too much of it. People journey down it. People write, dance and sing about it. People fight over it. And all people, everywhere and every day, need it.

--

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Gumara River (upper catchment), 2012

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Mekete Dessie Wosenie
Gent, May 2015.

Executive Summary

This study is undertaken in Lake Tana basin (Upper Blue Nile basin) in Ethiopia. An increasing number of water resource development projects (mainly hydropower and irrigation) take place on Lake Tana and in its catchment. Despite its potential for development and strong interest of the Government of Ethiopia to invest for the implementation of different water related infrastructures and services, Lake Tana and its basin are associated with various challenges. An example of such challenges is inadequate scientific knowledge on its basin characteristics, hydrology and climatic conditions. This work has emerged from such problems and triggered different research questions regarding runoff response of the major rivers in the basin, hydrological processes in the floodplain, discharge predictions for ungauged catchments, water budgets of Lake Tana and implications of the various water resources developments on the lake. The research aimed at a better understanding of the hydrology of the Lake Tana basin to contribute to sustainable management of land and water resources in the area.

Water level measurements were conducted in 15 stations on the tributaries of the lake (most of the stations were established on the major rivers of the Lake Tana basin). Pressure transducers (automatic water level recorders) and staff gauges were used to measure the river flow depths on a continuous basis. Rating curves were established to estimate discharges and the discharges obtained for the different catchments have been related to several catchment characteristics.

The largest part of the runoff in the majority of the monitored catchments took place in the form of flash floods (average flood duration lasting not more than 3-5 hours). Besides the temporal variability, high spatial variability of runoff has also been obtained. The total annual runoff coefficients ranged between 0.23 and 0.81 in 2012 in the basin. The highest runoff coefficient values were observed in the Gilgel Abay catchment. Catchment variations in terms of drainage density, topography, lithology, land use, and rainfall were found to affect the summer season runoff depth and runoff coefficients in the Lake Tana basin.

The floodplain abstracted 809 mm of water with a corresponding increase in floodplain storage of 992 mm during the beginning of the rainy season (June to July) and released

stored water starting from August until the middle of September in 2012. The floodplain acts as storage of flood water, and consequently the magnitude of peak floods was on average 71 m^3/s (or 30%) smaller downstream than upstream in the floodplain. The peak discharges of rivers in the floodplain of Lake Tana basin are buffered by the floodplain.

The hydrological model study results indicated that about 65% of the runoff appears in the form of interflow in the Gumara study catchment, and baseflow constitutes the larger proportion of runoff (44-48%) in the Gilgel Abay catchment. Direct runoff represents a smaller fraction of the runoff in both catchments (18-19% for the Gumara, and 20% for the Gilgel Abay) and most of this direct runoff is generated through the infiltration excess runoff mechanism from the impermeable rocks or hard soil pans.

Nearly 60% of the inflow to the lake is from the Gilgel Abay River. From the water balance analysis, the water budget components of the lake were found as a mean lake rainfall depth of 1330 mm, open water evaporation depth of 1789 mm, river inflow depth of 2201 mm and outflow discharge depth from the lake of 1618 mm. Annual flow reduction on the lake because of irrigation in the ungauged catchments was estimated as 42 mm. Simulated lake levels compare well with the observed lake levels ($R^2 = 0.95$) and the water balance can be closed with a closure error of 82 mm/year (3.5% of the total lake inflow).

The inflows to Lake Tana are estimated to reduce by about 27% when all planned water resources development projects are implemented in the basin. The full implementation of planned projects results in the generation of 460 MW hydroelectric power and about a billion m^3 per annum supply of water to the large-scale irrigation schemes. During low flow conditions, supply will run short of demands and the lake water level can drop by 0.3 m from the natural outlet level of 1785 m a.s.l.

The lake experienced four periods of different flow regulations since monitoring of the lake water level started. Generally, the lake levels have been increased significantly due to regulation with subsequent impacts on the lake ecology. However, following the implementation of Tis Abay II hydropower project in 2001, the lake level was reduced to its lowest recorded level in 2003. It was characterized by its noticeable consequences on the lake and its ecology including desiccation of reed beds and consequent loss of fish breeding habitat, extended crop production of the lake bed and navigation difficulty.

The outcomes of the this study contribute to proper planning and management of land and water resources of the Lake Tana basin and are believed to be applied by the different stakeholders involved in the basin. In this study, we generated additional data sets on runoff and sediment with better quality and coverage in the basin and can, therefore, be used by the stakeholders and the scientific community, who are involved in planning, design, and research activities in the basin and similar catchments in northern Ethiopian highlands. We developed a simple robust hydrological model which is based on catchment soil moisture status and topography and minimal model parameters. It can be used to estimate runoff volumes for the ungauged catchments by the engineers and planners for various preliminary water resource planning purposes. We have also addressed the impacts of the floodplain on river discharges and on water balance of Lake Tana. The results of this study, mainly on the water budgets of the lake and the hydrological processes of the floodplain, will have positive implications for those involved in the conservation and management of the ecosystem.

Key words: Lake Tana, floodplain, water balance, runoff, Blue Nile basin, scenario.

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List of symbols and acronyms

Symbol/ Acronym	Unit	Explanation
A_i	km^2	Incremental area
ANRS	-	Amhara National Regional State
A_r	km^2	Impermeable portion of the catchment area
A_t	km^2	Total catchment area
a.s.l	-	above sea level
ASTER	-	Advanced Space borne Thermal Emission and Reflection
BCEOM	-	Egis Bceom International
CSA	-	Central Statistical Agency
D	m	Soil depth
DEM	m	Digital Elevation Model
DSS	-	Decision Support System
E_a	mm/day	Actual Evapotranspiration
E_{lake}	mm/day	Lake evaporation
E_p	mm/day	Potential Evapotranspiration
ET_A	mm/year	Annual Evapotranspiration
ET_m	mm/day	Monthly Evapotranspiration
EWNRA	-	Ethio Wetlands and Natural Resources Association
G	-	Average slope gradient of a catchment
FAO	-	Food and Agriculture Organization
F_c	-	Field capacity of soil
GPS	-	Global Positioning System
GWP	-	Global Water Partnership
h	m	Water level
HDR	-	Human Development Report
HP	-	Hydropower
i	-	Hydraulic gradient
IEA	-	International Energy Agency
ICWE	-	International Conference on Water and the Environment
IDW	-	Inverse Distance Weighing
ITCZ	-	Inter-Tropical Convergence Zone
IWRM	-	Integrated Water Resources Management
K	mm/day	Permeability of the upper soil layer
k1	-	Parameter to relate discharge and storage for the groundwater
K_s	mm/day	Saturated hydraulic conductivity of soil
$K_{s,e}$	mm/day	Saturated hydraulic conductivity of the deep soil layer
$K_{s,u}$	mm/day	Saturated hydraulic conductivity of the upper soil layer
L	m	Average slope length
Mm^3	-	Million m^3
MoFED	-	Ministry of Finance and Economic Development
MoWR	-	Ministry of Water Resources

NMA	-	National Meteorological Agency
NOAA-CPC	-	National Oceanic and Atmospheric Administration - Climate Prediction Center
NSE	-	Nash-Sutcliffe Efficiency
OECD	-	Organization for Economic Co-operation and Development
P	mm/day	Precipitation
P_A	mm/year	Annual Precipitation
PBIAS	-	Percent bias
P_{lake}	mm	Lake areal rainfall
Q	m^3/s (mm/day)	Discharge
Q_1	mm/day	sum of direct runoff and interflow in the soil reservoir
Q_2	mm/day	baseflow from the groundwater reservoir
Q_d	m^3/s	Discharge at the downstream station
Q_f	m^3/s	Runoff in the floodplain area
Q_{gauged}	m^3/s	Gauged catchment inflow
Q_i	m^3/s	Discharge between the upstream and downstream stations
Q_{in}	m^3/s	Inflow into a reservoir
Q_{out}	m^3/s	Outflow from a reservoir
Q_p	m^3/s	Peak discharge
Q_r	mm/day	medium slope recharge from hillslope areas
Q_R	mm/day	Return flow
Q_{se1}	mm/day	Saturation excess surface runoff
QSe2	mm/day	direct runoff from impermeable surface of a catchment
Q_{ss}	mm/day	subsurface runoff
Q_u	m^3/s	Discharge at the upstream station
$Q_{ungauged}$	m^3/s	Ungauged catchment inflow
R	mm/day	Deep percolation
r	-	Pearson correlation coefficient
R_A	m^3/year	Annual Runoff
RMSE	mm/day	Root Mean Squared Error
S_b	mm	maximum available soil storage capacity
S_f	mm	Field storage capacity
S_g	mm	Ground water storage
SMEC	-	Snowy Mountains Engineering Corporation
SRTM	-	Shuttle Radar Topography Mission
TARC	-	Total Annual Runoff Coefficient
T_r	day	Response time
WASE	-	Water and Sediment
WHO	-	World Health Organization
WMO	-	World Meteorological Organization
UNESCO	-	United Nations Educational, Scientific and Cultural Organization
UNECA	-	United Nations Economic Commission for Africa
UNDP	-	United Nations Development Programme
UNICEF	-	United Nations Children's Fund

USGS	-	United States Geological Survey
V_{lake}	m^3	Volume of the lake
V_b	mm/day	Sub-surface flow velocity
WWDSE	-	Water Works Design and Supervision Enterprise
ϕ	-	Soil porosity
β	-	Model parameter for variability of permeability of soil
γ	-	Parameter for variability of percolation with soil water storage
λ	-	Coefficient that represents part of catchment that is impermeable
α1	-	Interflow partitioning coefficient for the steep slope surface
α2	-	Interflow portioning coefficient for the medium slope surface
ε	m^3	Uncertainty in the water balance terms of Lake Tana

CHAPTER 1

1. Introduction

1.1 Water resources and the need for sustainable management

1.1.1 Water availability and demand

Water is an essential natural resource for human beings and for ecosystem functioning. It is a finite renewable resource, of which the quantity and quality are both space and time dependent. Lakes and rivers, which have served as the major sources of water through most of human history, constitute less than 0.3% of nearly 3% of Earth's freshwater (Shiklomanov, 1993). The amount of freshwater on the planet has remained fairly constant over time and the main source of this fresh water is runoff, which is used extensively to satisfy widely varying human needs (Shiklomanov, 1993).

Global water consumption has nearly doubled since 1950 (UNESCO, 2003), and the demands for water resources continue to increase in response to population growth, greater prosperity and life quality, and the increasing needs of agriculture, industry, and other users (Postel, 1992; Gleick, 1993; Jackson et al, 2011). By the year 2025, 60% of the world population is expected to live in moderately to extremely vulnerable regions (Kulshreshtha, 1998). Furthermore, water-related infrastructure and services are inadequate in developing countries, thereby water related problems such as inadequate drinking-water supply and sanitation, water pollution, floods, the siltation of river systems, and the management of rivers and large dams are more prevalent in these countries than in the world's wealthier, industrialized ones. For example, in Africa about 65% of the population lack access to adequate water supply, and 73% are without access to adequate sanitation (UNECA, 2001). In a similar report issued in 2013 by WHO, 768 million people worldwide (most living in developing countries) were without access to an improved source of water (WHO, 2013). Likewise, the utilization of the water resources for generating electricity in such countries is also inadequate. More than 95% of the 1.3 billion people worldwide, who still lack access to electricity, are located in sub-Saharan Africa and developing Asia (IEA, 2012). Therefore, the demands for freshwater and energy will be more acute over the coming decades in developing countries, that are undergoing accelerated transformation and rapid economic growth. According to Kumar et al. (2011), the percentage of undeveloped technical potential for hydropower is highest in Africa, and water as a source of power has a vital role to play in responding to the socio-economic crisis facing Africa.

Ethiopia, endowed with ample water resources, has 12 river basins with an annual runoff volume of 122 billion m^3 of water (75% drains to neighboring countries) and an estimated 2.6-6.5 billion m^3 of groundwater potential (Awulachew et al., 2007). However, very little of the available water resource has been used for agriculture, irrigation, hydropower generation, and industrial purposes. Agriculture is mainly rain-fed in Ethiopia, which is affected by the highly variable rainfall and recurrent drought. Rainfall across much of the country is highly seasonal (most of the rain falling in a single, short season) with high variability and unpredictable nature, both in time and space. According to World Bank (2006), the economic cost of hydrological variability for the nation is estimated at over one third of the nation's average annual growth potential and yet the country has less than 1% of the artificial water storage capacity per capita to manage that variability. It has one of the lowest reservoir storage capacities in the world, 50 cubic meters per person compared with 4,700 in Australia (UNDP/HDR, 2007/08).

From the estimated potential irrigable land of 3.7 million hectares, less than 5% of this potential is developed for irrigation (FAO, 2008; World Bank, 2006), despite the acute shortage of food in the country. Moreover, access to an improved water source and improved sanitation was estimated, respectively, as 38% (98% for urban areas and 26% for rural areas) and 12% (29% in urban areas, 8% in rural areas) in 2008 (WHO/UNICEF, 2008).

Per capita electrical consumption is very low in the country, whereby only 1-3 % of the estimated 30,000 MW hydropower potential is exploited (Solomon, 1998; Feibel, 2003). According to IEA (2008), the current energy consumption is 92.4% from waste and biomass, 6.7% from oil, and 0.9% from hydropower. An estimated 12% of the Ethiopian population (2% of the rural, despite almost 85% of the Ethiopians living in rural areas) has access to electricity (World Bank, 2008).

Water resources development and management remain an urgent priority of the struggle for growth, sustainable development and poverty reduction in the country. In response to this, the Ethiopian government has been involved in the construction of infrastructures and facilities, particularly hydropower and irrigation schemes, to stimulate economic growth and reduce poverty (MoFED, 2006). To this end, Lake Tana (i.e. largest natural lake in Ethiopia) and its basin have been identified as one of the growth corridors in the country in line with its significant potential for water, land, livestock, forest and fishery resources; its rich cultural heritage and natural assets; the relatively developed urban centers and dense settlements; and the good roads and air connectivity.

To make use of its water resources potential for growth, various water resources development schemes are being implemented in the basin (World Bank, 2006). The Tana-Beles hydropower project, which transfers water from Lake Tana to the Beles River via a 12 km long tunnel and generates 460 MW of electricity, has been in operation since 2010. Irrigation schemes to irrigate more than 70,000 ha are planned (some are under construction) on the main rivers flowing into Lake Tana. Other private investments in agriculture, agro-industry, hotels, tourism, and micro-enterprises are taking place around Lake Tana. Yet, they are implemented in a fragmented manner without a clear coordination mechanism for integrated development. Recent studies conducted for Eastern Nile Basin countries indicate that water resources vulnerability is found to be high in Ethiopia (Hamouda et al., 2009). Therefore, the success of all the upcoming and current water resources projects depends on the sustainable management, planning and use of the water resources in the basin.

1.1.2 The need for sustainable management and its constraints

Due to increased pressures on water resources across the world, the use of the Integrated Water Resources Management (IWRM) concept for effective and efficient management of water resources worldwide has been promoted since the United Nations Conference on Water in 1977. The Technical Advisory Committee of the Global Water Partnership emphasized that water should be managed in a basin-wide context, under the principles of good governance and public participation (GWP, 2000). Although implementing water resources in an integrated manner is important, its management is complex. Effective coordination and integration between the water system and other systems need efficient decision and controlling mechanisms, which in turn demand profound understanding and knowledge of the system. Despite its potential for development and strong interest of the Government of Ethiopia to invest for the implementation of different water related infrastructures and services, Lake Tana and its basin is associated with various challenges, which can end up in failure to the sustainable development and management of the resources in the basin if not properly addressed. Some of the challenges are discussed below that demonstrate the need for additional scientific insights in the Lake Tana system.

a) Land degradation, soil erosion and sedimentation

Extensive catchment degradation driven by population growth, deforestation, overgrazing, low levels of technology and improper land management practices have reduced the productive capacity of land in the basin and its carrying capacity (Nyssen et al., 2004). The northern Ethiopian highlands are among the most seriously affected regions by soil erosion (Nyssen et al., 2004). This soil erosion coupled with heavy use of fertilizers on the upland catchment results in sedimentation and eutrophication of the Lake Tana and accordingly storage volume reduction of the lake that can have far reaching negative consequences for economic activities; hydropower, tourism, fishery and biodiversity. In the main rainy season, the tributary rivers carry heavy loads of suspended silt into the lake and increase the turbidity of the lake water (Vijverberg et al., 2009). The combined impact of increased sediment loads and deposition, and conversion of wetlands into agricultural land that provide a natural filtration capacity for sediment and contaminant loads is reducing the lake’s natural buffering capacity to deal with such stresses (World Bank, 2006)

b) Lake level fluctuations, competition for water during shortage and floods

Along with the implementation of various water resources projects, competition for use of the water and between the different users in the basin is increasing. During the dry season, there is high abstraction of water for smallholder irrigation in the floodplain along the major river courses in the basin. Consequently, the river flows in the very downstream reaches of these rivers can even cease with significant consequences on the downstream utilizers (Fig. 1.1a).

Lake level regulations have made the lake level to fluctuate yearly by about 2 m (See details in Chapter 6). Depending on the seasonal rainfall and water demands, the lake levels can drop below its natural outlet level. During the 2003 drought, the already shallow lake level (average depth ca. 9 m) dropped by 0.6 m from its natural outlet level and lake surface area was reduced by 35 km^2, aggravated by hydropower generation demands (World Bank, 2006). Owing to such excessive drop of the lake level, navigation was interrupted for some months during this year. Future climate change is expected to aggravate this variability and further increases the uncertainties that currently impact livelihoods and investments in that area. Therefore, variations in lake levels beyond some threshold levels can cause conflicts among the different users (hydropower, navigation, tourism, fisheries and environment). Moreover, the upcoming irrigation projects in the Lake Tana basin are another strain to the lake and to the basin as a whole.

Challenges in the Lake Tana area are not limited to the case of shortage of water availability, but also when there is excess of it. Floods, as a result of rise in lake levels and overbank flow of the tributary rivers in the downstream reaches during the rainy season, are becoming frequent, with tremendous effects (Fig.1.1b). During flooding in 2006, more than 15,000 ha was inundated, 10,000 people were displaced, 2500 domestic animals swept away, and many houses were demolished.

Figure 1.1: (a) Dry Rib River bed due to excessive upstream water abstraction in April, 2012 and (b) Gumara River overbank flooding in the floodplain during the rainy season.

c) Inadequate scientific knowledge of the lake and its basin

Research efforts made so far in the basin and on Lake Tana as well as in the Upper Nile basin with respect to basin characteristics, hydrology and climatic conditions are scanty (Johnson and Curtis, 1994; Conway, 1997; Antar et al., 2006), fragmented and also controversial. There have been attempts to understand hydrological processes and climatic conditions in the Upper Nile basin as well as in Lake Tana basin. All attempts are, however, constrained by limited data availability and reliability. In line with the low density of river discharge gauging stations, estimates of inflow contributions of ungauged catchments to the Lake Tana by the different researchers is controversial: 7% (Kebede et al., 2006), 29% (SMEC, 2007) or even more than 42% (Wale et al., 2009). The magnitude of the various water balance terms of Lake Tana and their uncertainties are critical as water resources can be neither developed nor managed rationally without an assessment of the quantity and quality of water available (UNESCO/WMO, 1988).

Water quality studies in the Lake Tana basin are limited. A number of studies have been carried out on soil erosion and sediment yield of the basin (e.g. Awulachew et al., 2008; Shimelis et al., 2008; Sutcliffe and Parks, 1999). However, due to differences in assumptions, estimations of sediment amounts entering the lake are highly variable. In SMEC (2007), it is reported that the rate of sedimentation in the lake is in the order of 1 to 2 mm/year. Indications of pollution of the lake have also been reported (Teshale et al., 2001). Siltation is common in the downstream reaches of the major rivers, which is one of the causes of overbank flow and flooding.

Lake Tana is associated with an extensive floodplain adjacent to the lake and its lowland tributaries (Fig. 1.2). The floodplain is the hydrological connector between the lake and the upper catchments, and affects the water balance of and sediment flux into the lake. However, very little is understood about the hydrological processes in the floodplain and its effects on the river discharges and consequently on the water balance of the lake. Almost all the water balance studies of the lake undertaken so far did not differentiate runoff estimates between the floodplain and the upland catchments. The aforementioned discussions substantiate the need for a comprehensive study in Lake Tana basin that quantifies water and sediment budgets, considering the existing and upcoming land and water development initiatives in the basin based on additional and reliable data.

Figure 1.2: A view to the floodplain in the Lake Tana basin during the rainy season (August, 2014)

d) Data availability and data base establishment

One of the major bottlenecks for development is the lack of a sufficient scientific database and the lack of appropriate methodologies and strategies. Among others, collection and documentation of reliable hydrometeorological data is one of the pre-requisites for any water resource development intervention. Consequently, there is a large need for measured data on runoff and sediment yield in Northern Ethiopia for many purposes (e.g. reservoir construction, flood control, irrigation).

While data on precipitation, which can be measured with relative ease, are generally available for most countries (also for Ethiopia), river runoff and groundwater levels are generally much more difficult and costly to monitor. In the Lake Tana basin, there are about 40 rainfall stations (the majority are non-recording type). Based on the World Meteorological Organization criteria (WMO, 1994) for mountainous areas, the rainfall stations covered not more than 70% of the basin area. Considerable areas in Gilgel Abay, Rib and Gumara catchments as well as the lake surface appeared to be poorly covered by the stations. River discharge data from gauged catchments are also available from Ministry of Water, Irrigation & Energy for the major rivers in the basin, but need to be scrutinized because of rising river bed and sedimentation at gauging station sites which affects the rating curve (Fig. 1.3). However, discharge data are available for about 42% of the catchment area in the basin (SMEC, 2008). This has contributed a significant share to blur the understanding and better determination of the available water supplies in the basin. The lack of information on the supply and demands of water resources poses a risk on the management of water resources, especially in terms of priority decision making.

Figure 1.3: Staff gauge section at the Gumara station (source: SMEC, 2008). In this study, this station has been replaced by a new installation further downstream along this river.

To meet the governmental objectives and peoples' urgent demand, it is important to understand the magnitude, spatial variability and temporal dynamics of the runoff and sediment transport processes in the Ethiopian highlands at the catchment scale and to develop runoff and sediment yield assessment methodologies in this region.

Therefore, this study is conducted in the Lake Tana basin to shed light on some of the problems and to contribute to the better (optimized) management of water resources in the basin. This work has emerged from the Wase-Tana Project (http://geoweb.ugent.be/physical-geography/research/wase-tana) to handle the hydrological part of the project objectives in the basin.

1.2 Research questions and objectives

1.2.1 Objectives

In order to address some of the problems discussed in the previous section and to fill the knowledge gap in understanding the hydrology of the basin in particular, the study described in this dissertation has the following objectives.

a) Overall objective

The overall objective of this study is to improve our understanding of the hydrology of the Lake Tana basin in order to better plan and manage its water resources for a sustainable development.

b) Specific objectives

The specific objectives of this study are:

i. to assess the temporal (daily and seasonal) and spatial (between catchments) variations of runoff in the Lake Tana basin;
ii. to assess the effects of the floodplain on river discharges into the lake;
iii. to develop a conceptual hydrological model and analyze rainfall-runoff processes in the basin;
iv. to establish water budgets of the lake and to simulate lake level changes under different scenarios; and
v. to assess the impacts of upcoming water resources development projects in the basin on the lake for supporting decisions in the planning, management and water allocation strategy of the different water use sectors.

1.2.2 Research questions

Based on the general and specific objectives of this dissertation, the following research questions are formulated:

i. Spatial and temporal variations of runoff (river discharges)
    1. What is the variation of the runoff response to rainfall over the major catchments in the basin?
    2. What are the different catchment characteristics (topography, lithology, land use, etc.) that can explain the runoff variables (total runoff, runoff depth, or runoff coefficient) in the Lake Tana basin?
    3. How can we conceptualize the hydrology of the floodplain? What is the impact of the floodplain on river discharges into the lake?

ii. Hydrological modeling
    1. Can we model the rainfall-runoff processes of the basin using simple models? Can we identify the prevalent runoff mechanism and quantify the magnitude as well as the variability of the different discharge components (direct runoff, subsurface runoff and groundwater flow) among the different catchments of the major rivers in the basin?

   2. How reliable is the application of the hydrological model, which is developed and tested for the gauged catchments in the basin, to other ungauged catchments for the prediction of discharge?

iii. Lake water balance

   1. What is the water budget of the lake and how does the floodplain buffering affect the water balance of the lake?
   2. Which parts of the lake basin generate most of the runoff to the lake? How are the different uncertainties in the water balance terms of the lake explained and compared with previous studies?

iv. Decision Support System (DSS)

   1. Can we develop a water resources decision support system (DSS) framework that allows for optimal allocation of water resources among the different water use sectors in the basin?
   2. How will the lake level be affected under various hydrological conditions and different water resource developments in the basin?

1.3 Dissertation outline

This dissertation is structured in line with the research objectives and to address the research questions presented above. The dissertation has seven chapters. In chapter 1, a wider context for the research is provided by highlighting some of the critical water resources issues worldwide, and in developing countries in particular. The various water resource challenges of the study basin, the objectives of this research and the research questions are presented in this chapter. Chapter 2 describes the environmental settings of the study area. It begins with the presentation of the whereabouts of the study area in terms of its geographic, local and regional settings. This is followed by sections on geology, soil and land cover types of Lake Tana basin. An overview of the climate and hydrological systems of the study area is also included. The status of water resources development in Ethiopia in general, and Lake Tana basin in particular, is briefly presented in the last part of the chapter.

Chapters 3, 4, 5 and 6 deal with the assessment of different hydrological processes in the Lake Tana basin and the impacts on its water resource management. Chapter 3 addresses the hydrology of the floodplain along with the spatial and temporal variation of the runoff in the basin. This is an important part of the research which takes care of the research questions outlined in (i) under Section 1.2.2. Analysis of rainfall and runoff is made and explanatory factors for variations of runoff in the basin are presented. Lake Tana basin hosts a substantial size of floodplains with their important hydrological and ecological functions. This chapter provides a description of the prevalent hydrological processes in the floodplain. Chapter 4 is dedicated to the development of a conceptual rainfall-runoff model relevant to the basin. The different hydrological processes, input requirements and outputs of the model are described. It starts with a detailed description of the hydrological model structure, followed by the model application for selected catchments in the basin and analysis of results to answer research questions stated in (ii) under section 1.2.2. Chapter 5 takes up the determination of the water balance of Lake Tana, one of the drivers of this study. The major water balance components of Lake Tana include direct rainfall, evaporation, inflow from gauged and ungauged catchments, and surface outflow. Computations of the water balance of the lake are challenged by the fact that most of the rivers in the floodplain are ungauged, and hydrological processes in the floodplain are different from that in the hillslopes. This chapter addresses the impact of the floodplain on the water balance of the lake and discusses research questions shown in (iii) under Section 1.2.2.

There is an increasing trend for water demand in the Lake Tana basin, owing to the implementation of different water resource projects in the basin. This needs an appropriate decision support system (DSS) to maintain reliable and optimal allocation of water for the different water use sectors in the basin. Chapter 6 is devoted to the formulation of this decision support framework. The implications on the lake levels when all the planned water resource developments in the Lake Tana basin are implemented are presented in this chapter. Answers to research questions outlined in (iv) under Section 1.2.2 are forwarded. Finally, summary of the main results, overall conclusion and perspectives are presented in chapter 7. Key contributions of the study and brief notes on identified areas for further research are included.

CHAPTER 2

2. The study area

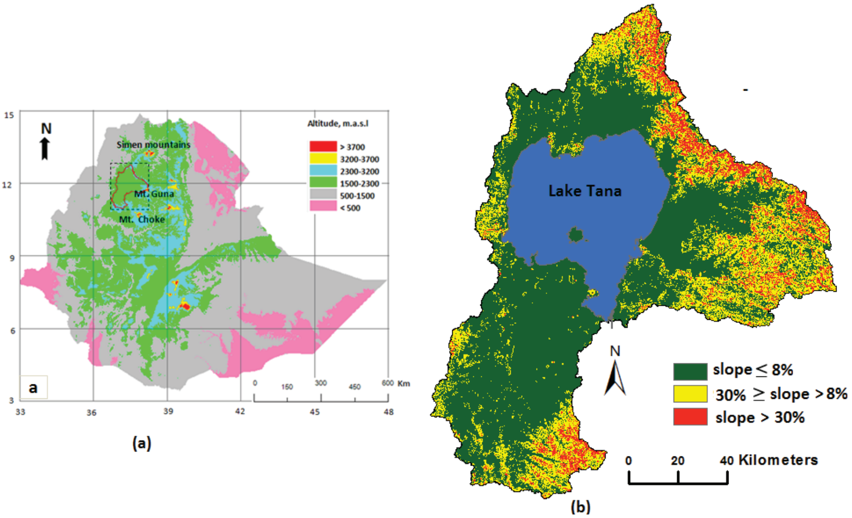
2.1 Location

The Lake Tana basin is located in the northwestern plateau of Ethiopia, and it extends from 10.9ºN to 12.8ºN latitude and from 36.7ºE to 38.3ºE longitude (Fig. 2.1). Lake Tana, the largest lake in Ethiopia, comprises the headwaters of the Blue Nile River basin (Abay basin) that flows from the Ethiopian highlands to the border between Ethiopia and Sudan generating about 60% of the main Nile River flow (Sutcliffe and Parks, 1999).

2.2 Overview of the Lake Tana basin characteristics

The total catchment area of the Lake Tana basin is 15,077 km^2, of which 3,077 km^2 (at 1786 m a.s.l) is occupied by the lake's water surface. Lake Tana lies in a wide depression in the Ethiopian Plateau and it is bordered by low plains (acting as floodplains) with mountain regions in the west and north-west (Fig. 2.1). The mean altitude of the basin is 2026 m a.s.l. with about 90% having elevation in the range 1780-2500 m a.s.l. Some areas close to the watershed divide have altitude ranging between 2500 and 4100 m a.s.l. (one of the highest mountains in Ethiopia, Mount Guna, is located at extreme east of the basin).

The downstream part of the basin is mostly either flat or gently undulating, making a large tract of floodplain around Lake Tana. The middle part has mainly rolling or hilly relief, and the upper part is dominantly steep (slope >30%) with limited mountainous and dissected land close to the watershed divide (Fig. 2.1b).



(a)

(b)

Figure 2.1: Location and topography of Lake Tana basin; (a) elevation relative to other regions in Ethiopia (adapted from Engida, 2010) and (b) slope of the Lake Tana basin.

Lake Tana is located in fault-bounded grabens (Mohr & Rogers, 1966; Chorowicz et al., 1998). There are three grabens in the Lake Tana basin (Fig. 2.2), forming a triple junction at Lake Tana (Mohr & Rogers, 1966; Chorowicz, 2005). In the north-northwest of the basin lies the Gondar graben, in the east the Debre Tabor graben, and in the south-southwest the Dengel Ber graben (Fig. 2.2). Kebede et al. (2005) indicated that the Lake Tana graben plays an important role in controlling the groundwater flow path.

The entire catchment of the lake is constructed out of lavas and the lake itself is formed by combined action of volcanism and faulting (Poppe, 2012). The basin is surrounded by denuded shield volcanoes to the east (Mount Guna) and south (Mount Choke), and by the West Tana escarpment to the west (Chorowicz et al., 1998). Lithologicaly, the basin consists of three lithostratigraphic groups (Poppe et al., 2013): Quaternary sediments, Quaternary igneous rocks and Tertiary igneous rocks (Fig. 2.3).

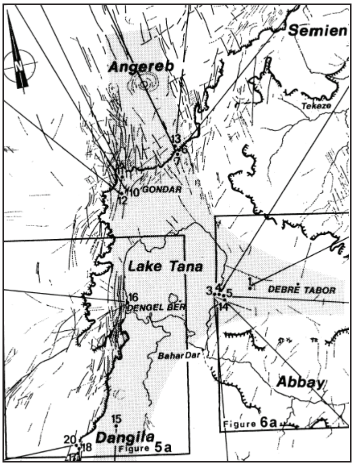


Figure 2.2: Inferred three-graben junction, indicated in grey (Source: Chorowicz et al., 1998).

The Quaternary sediments comprise alluvium, colluvium, and marshy lacustrine plains can be linked to earlier higher lake levels (Poppe et al., 2013). Alluvial sediments, which are composed of fine and coarse grained materials, are found in the lower reaches of the main rivers and the floodplains. The present floodplains (the Fogera plain and the plain near Gorgora in the north of the basin) are covered up with a thick pack of sediments. Lacustrine deposits are observed in the eastern and northwestern parts of the basin. Stiff and compacted sediment deposits with at least 50 m depth are also noted beneath the Lake Tana floor (Lamb et al., 2007).

The Tertiary Lavas (The Trap series) are situated in the northern part of the basin and make up more than half of the catchment. Within these trap series two shield volcanoes are located: Mount Guna and Mount Choke (Kebede, 2013).

The Quaternary lavas (Aden series) cover a large area (at least 3000 km² south of Lake Tana), and also Dek and Daga islands in the lake are formed by these more recent lavas (Mohr, 1962). The Quaternary lavas in the Lake Tana basin have helped to form the lake by their blocking to the south of the basin (Mohr, 1962).

In line with the geology of the basin, there are at least four major categories of aquifers in the Lake Tana basin: the Tertiary volcanics (upper basalt sequence and shield volcanics), Quaternary volcanics, Miocene sediments, and the alluvio lacustrine sediments (Kebede, 2013).

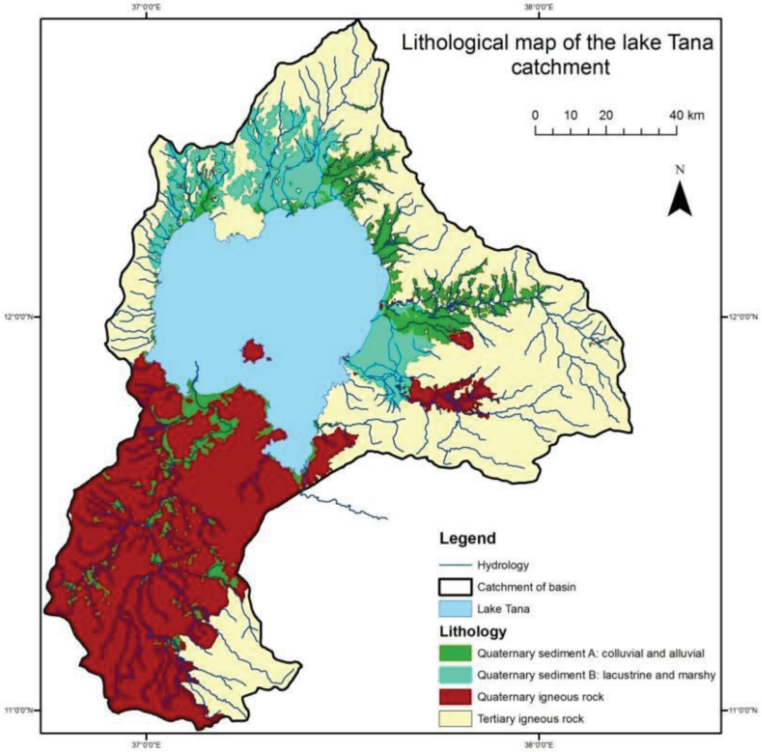


Figure 2.3: Lithological map of Lake Tana catchment (Source: Poppe et al., 2013)

The Tertiary basalts and recent lava flows which are widely distributed in the basin are grouped as extensive aquifers (BCEOM, 1999). According to SMEC (2007), the Tertiary basalt aquifers generally have transmissivity in the range of 0.1 to 32 m^2/day. The productivity of this aquifer is controlled by the intensity of fractures in the rock mass.

Quaternary basalts, underlying most part of the Gilgel Abay catchment (Fig. 2.4), are the most productive aquifer systems and are characterized with plenty of vesicles and are highly weathering (Kebede, 2013). The existence of relatively high discharge springs and wells implies its potential for bearing of high groundwater supply (e.g. the major springs of Areke and Lomi, sources of Bahir Dar city water supply, emerge from this aquifer unit with 140 and 50 l/s respectively).

The Miocene Lacustrine deposits, which are composed of clay, silty claystone, silty sandstone volcanic ashes and lignite beds, lie in the northern part of Lake Tana (Chilga-Gondar graben). It is reported that the thickness of the lacustrine deposit reaches 90 m and wells drilled in these sediments turned out to be dry (Kebede, 2013).

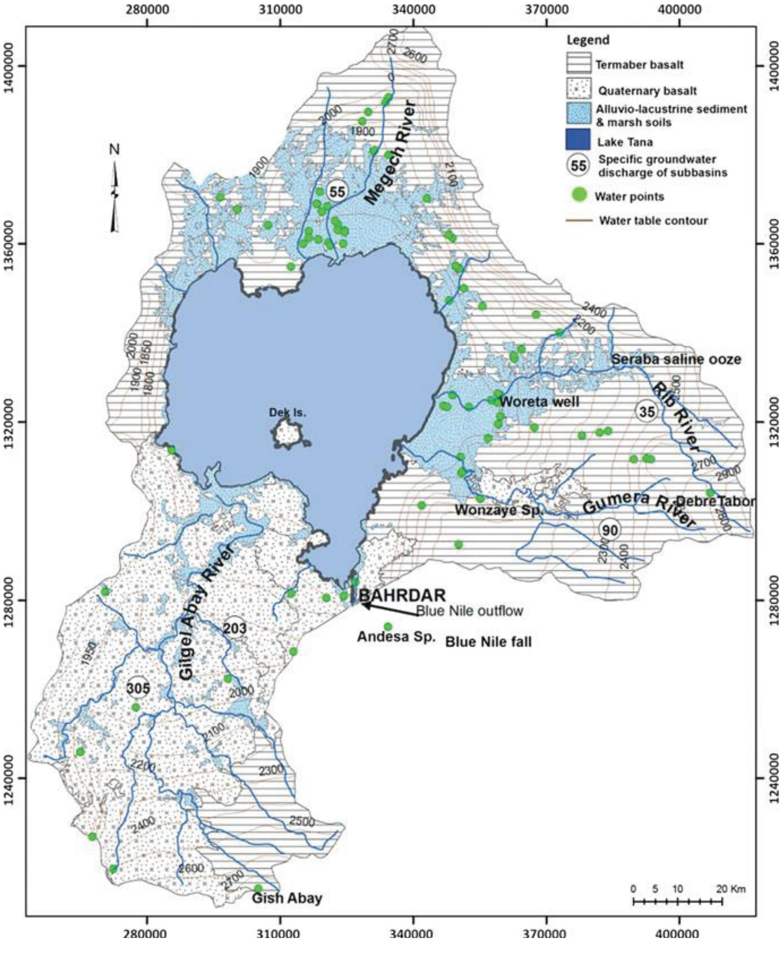


Figure 2.4: Hydrogeological features of the Lake Tana basin (adapted from Kebede, 2013)

Alluvial sediments are widely distributed along the lower reaches of the Megech, Rib and Gilgel Abay Rivers (Fig. 2.4). The thickness reaches more than 50 m with relatively low aquifer transmissivity and the aquifer properties are highly variable laterally (SMEC, 2007; Kebede, 2013).

There are also geothermal waters in the Lake Tana graben (mostly known are the Wanzaye thermal waters and the Andasa springs on the Bahir Dar to Blue Nile Falls road). The occurrence of faults and dikes in the basin enabled the thermal waters to appear on the surface of the ground penetrating through the basin aquifers (Kebede, 2013).

Based on piezo-metric level data, SMEC (2007) showed that groundwater flow direction is consistent with the surface water drainage. Groundwater flow is generally towards the lake from all directions and towards the rivers and wetlands. The downstream reaches of the major river systems (including the vast floodplains) are characterized by low hydraulic gradient and the water table is close to the ground surface (Kebede, 2013).

Poppe et al. (2013) reported that river drainage in the Lake Tana basin was radially divergent before formation of the lake. Convergence of the three grabens under the present lake reversed river drainage at several places. Rivers in the hilly areas are generally bedrock rivers, whereas in the floodplain meandering and sometimes braided rivers occur (Poppe et al., 2013).

The most important agents of landscape change now are humans and rivers (rivers input a high amount of sediment into the lake, which causes deltas to grow). This is due to greater population pressure and consequently more intensive cultivation with poor land use practices, resulting in high rates of soil erosion and land degradation. This is also evident from the high sediment load (Fig. 2.5) which shows that the rivers remove a lot of sediment from the mountains. This sediment is then deposited into the floodplain, the delta and the lake (Abate et al., 2015).

Most soils of Lake Tana basin are expected to be derived from basalt weathering. Based on the FAO soil classification system, ten types of soils are identified (Fig. 2.6). About 70 % of the basin is covered by four major soil groups: Luvisols, Leptosols, Vertisols and Fluvisols. Nitisols dominate the higher parts of the landscape and on slopes. On the other hand, Vertisols are found in the local depressions or on stable terraces. Closer to the lake, Vertisols are available and based on Hendricksen et al. (1984) such soils have developed on alluvial sediments. The lacustrine deposits, as well as the weathering materials of the basalts, yield fertile soils for Ethiopia. The majority of the study area has deep to very deep soil depth (BCEOM, 1998a) with hillslopes having a thin soil layer.

Figure 2.5: Megech River flood water carrying a lot of sediment in 2013

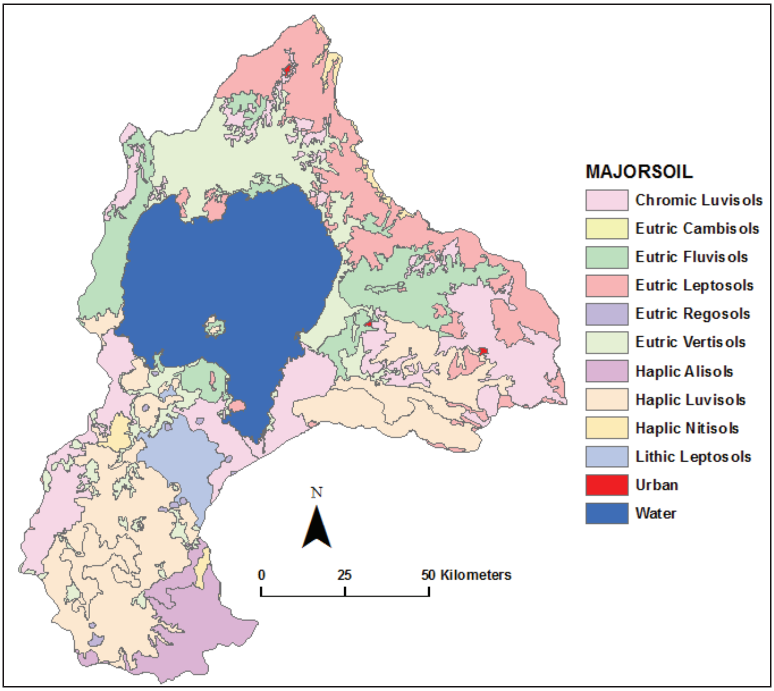


Figure 2.6: Soil distribution in Lake Tana basin (Source: BCEOM, 1998a).

Agriculture is an essential sector for the country. 81% of the economically active Ethiopian population works in this sector (Aquastat, 2005). The Lake Tana basin is one of the regions with high agricultural productivity as compared to the rest of the country.

The main land use is cropland. Mixed farming and agro-pastoral systems are the most present production systems in Lake Tana basin. The main crops are cereals, pulses, oil crops, khat and some vegetables. The major cereals cultivated in the region are teff, finger millet, rice, wheat, maize, barley and flax. Other land cover types include grasslands, open shrublands and plantation, mainly eucalyptus.

Soil tillage in the Ethiopian highlands is mostly done by the use of the *marasha*. This tool is pulled by a pair of oxen to break the ground, providing a weed-free seedbed and enhanced infiltration (Temesgen et al., 2008). Repeated tillage is required due to the incomplete, V-shaped plowing. A poor soil structure, crust formation and plough pans are undesirable outcomes (Biazin et al., 2011). Conventional tillage in the Ethiopian highlands includes for most of the crops a minimum of three tillage operations (Araya et al., 2012): twice before sowing (before the onset of rain, and after first rain shower) followed by one superficial tillage operation after the seeds are broadcasted (Gebreegziabher et al., 2009).

The land management practices in the study area are strongly related to the highly seasonal rainfall pattern. With guidance from the Regional Bureau of Agriculture, stone bunds are implemented in specific areas in Lake Tana basin (Fig. 2.7).

Figure 2.7: Stone bunds in the Lake Tana basin as soil and water conservation practices, 2014

The slope of the area is one of the decision criteria such that erosion control has to start from the above steep slope, taking gradually the lower areas into account. The construction of stone bunds is a time-consuming and a though labor task. Nevertheless, farmers realized that the construction of stone bunds is the best way to prevent soil erosion on sloping farmland.

Drainage ditches (*feses*) are established during the rainy season on sloping farmland for different reasons. It is indicated by Monsieurs et al. (2014) that drainage ditches are perceived as the best conservation practice (also generate high runoff response) if no stone bunds are present. It is a common practice in the basin to implement stone bunds as well as *feses* on cropland. The malfunctioning of stone bunds or an excess of water that needs to be drained away are reasons mentioned by the farmers for the use of a mixed land management. In the Lake Tana basin, positive effects for surface runoff and soil loss have been found by applying stone bunds (Brenner et al, 2013).

Deteriorating soil fertility and declining landholding sizes, because of population growth, are among the biggest challenges facing the production system (Aquastat, 2005). Overgrazing, deforestation, improper land management practices and low access to inputs and technology, are some other reasons which have caused extensive land degradation in the catchment and have reduced the productive and carrying capacity of the land in the basin (Nyssen et al., 2004; Amsalu et al., 2007). This results in higher sediment loads in the rivers, more fluctuating flow inputs to the lake and a decreased water storage capacity, due to the sedimentation in the lake (Zegeye et al., 2010).

2.3 Hydrology and the water resource potential for development

Ethiopia has 12 river basins (Fig. 2.8), which altogether generate an annual runoff volume of 122 billion m^3 and with a renewable groundwater potential of 2.6 billion m^3 (MoWR, 2002).

Lake Tana and its basin comprise the headwaters of the Abay Basin (Upper Blue Nile basin). Abay basin (Fig. 2.8) is the most important river basin in Ethiopia, which occupies 17.5% of Ethiopia's land area. The basin has an average annual runoff estimated to 54.8 billion m^3, representing about 50% of the country's total average annual runoff, 25% of its population and over 40% of its agricultural production (Awulachew et al., 2007).

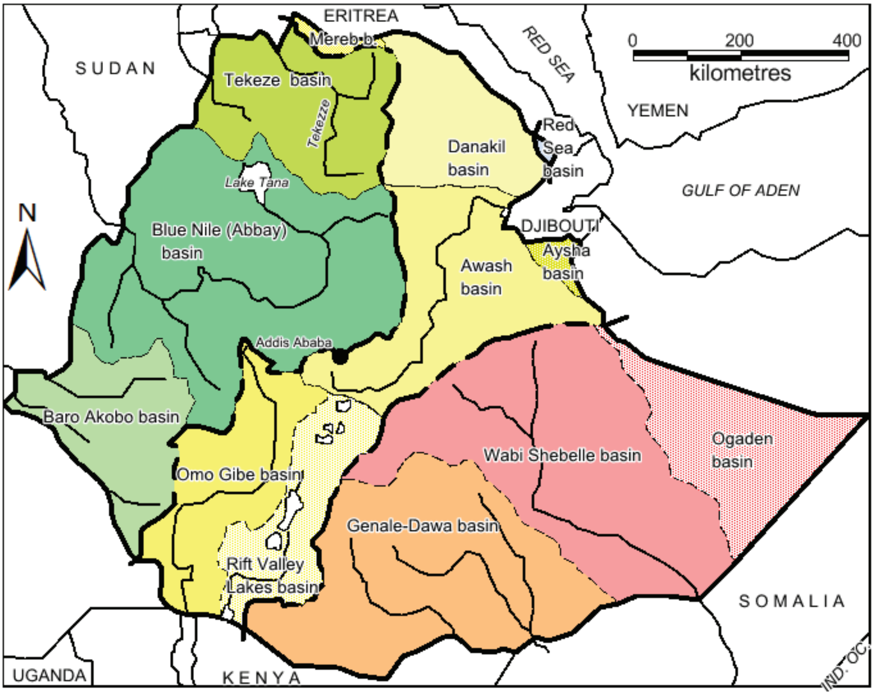


Figure 2.8: River basins of Ethiopia (adapted from Nyssen et al., 2010). The bold dashed lines represent major water divides between the Mediterranean Sea basin (west), the Rift Valley endorheic basins (center), and Indian Ocean basin (east)

The Abbay basin accounts for a major share of the country's irrigation and hydropower potential. It has an irrigation potential of 815,581 ha and a hydropower potential of 78,820 GWh/y (Awlachew et.al. 2007).

Lake Tana basin consists of more than 40 different tributary catchments of varying sizes that all drain into the lake (Fig. 2.9). However, four rivers, namely Megech, Rib, Gumara and Gilgel Abay provide more than 90% of the runoff received by the lake (Kebede et al., 2006). Dessie et al. (2015) and also Chapter 5 in this dissertation further showed that about 60% of the runoff to the lake is contributed from the Gilgel Abay catchment. Runoff is very seasonal in the basin depending on the rainfall and more than 70% of the annual volume of runoff is concentrated in the *Kiremt* (rainy) season. Following the rainy season, flooding of low-lying areas is a frequent problem due to overtopping of major river banks and rising of the lake level (SMEC, 2008).

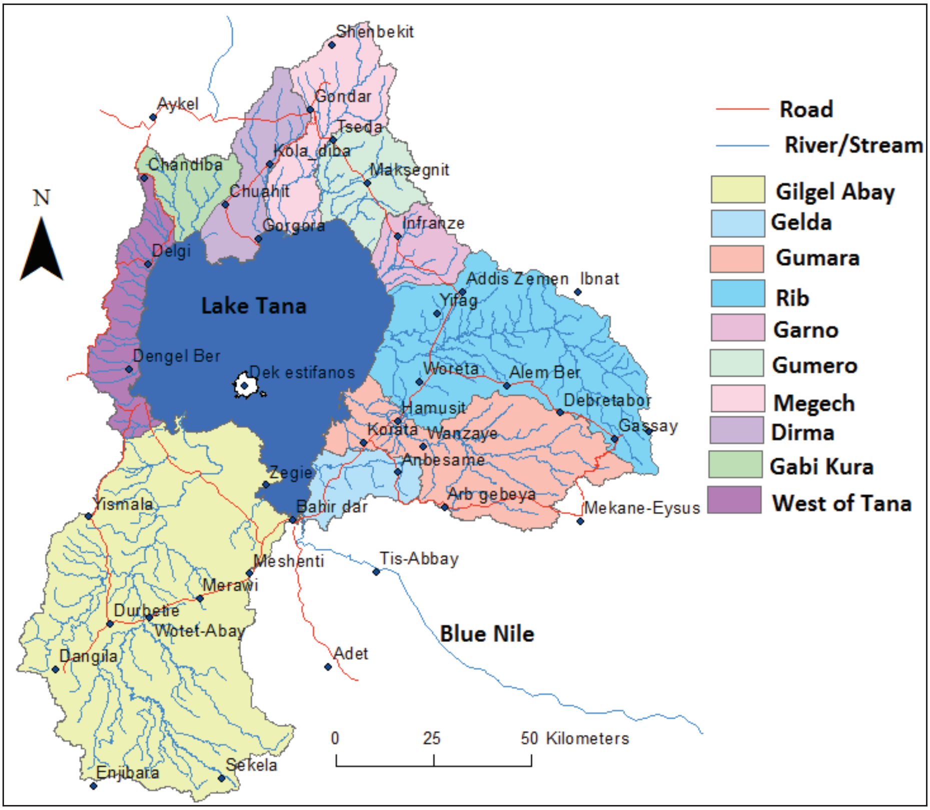


Figure 2.9: Major hydrological systems of Lake Tana basin

Lake Tana is a shallow lake with an average depth of 9 m. The outlets of the lake are the Blue Nile (natural surface outflow at the southern shore) and a tunnel hydropower outlet. The outflow from Lake Tana contributes about 7% of the Blue Nile flow at the Ethio-Sudanese border (Conway, 2000). The 2012 and 2013 years lake outflow data (Ethiopian Ministry of Water, Irrigation and Energy) show that the average annual outflow to the Blue Nile at the southern shore has dropped to 75 m^3/s (flows as low as 1.9 m^3/s are observed in the years), due to the regulation and diversion of the lake water to Tana Beles hydropower plant, in contrast to its average annual outflow of 133 m^3/s before the operation of the Tana Beles hydropower plant (outflow data for years 1995-2006).

The lake is bordered by low plains (acting as floodplains) with mountain regions in the west and north-west. The largest area of the floodplain in the Lake Tana basin is located in the northern and eastern parts of the basin, following the downstream reaches of the Gumara, Rib and Megech Rivers. The floodplain consists of permanent swamps, seasonal swamps, and areas subjected to regular inundation. Total area of seasonally inundated land is in the order of 450 km^2 (SMEC, 2007); the extent of flooding is dependent on the rainfall, the magnitude of river flooding and the lake level.

Lake Tana and its basin are endowed with enormous potentials for development like water transportation, fishery, hydroelectric power generation, irrigation, livestock development, tourism and recreation. Although the extent of irrigated land in the basin is currently low, different studies estimate the potentially irrigable area in the basin to be more than 120,000 ha (BCEOM, 1998b; Wale et al., 2013). From the large scale irrigation projects planned in the basin, only the Koga irrigation project is operational to irrigate 7000 ha. Recently, the Tana-Beles hydropower project has been implemented to generate 460 MW of hydropower and irrigate more than 100,000 ha of land in another basin (Beles basin) by diverting the lake water through a tunnel. For this purpose, an important low-height hydraulic structure (Chara Chara weir) has been built at the natural outlet of the lake to regulate the outflow of the lake.

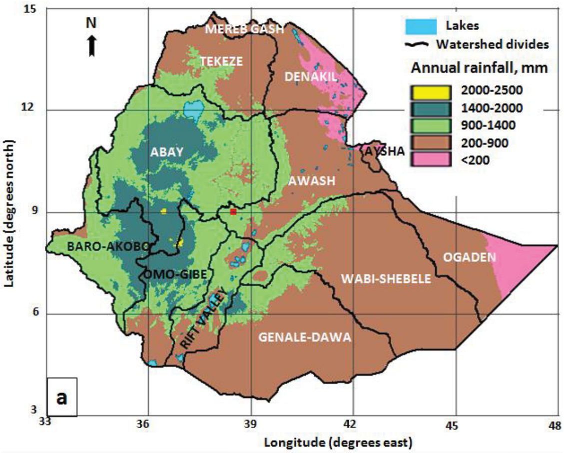
2.4 Hydrometeorological data

2.4.1 Climate

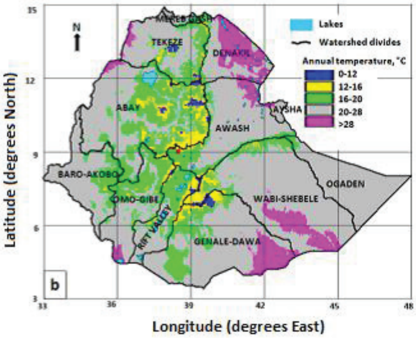
The rainfall pattern in Ethiopia is dominantly controlled by the migrating inter-tropical convergence zone (ITCZ), making it highly seasonal (Hulme, 1996). Moreover, the spatial and temporal patterns of rainfall in Ethiopian highlands are affected by orographic and convective factors (Korecha and Barnston, 2006).

Depending on the rainfall, there are three seasons in Ethiopia, namely *Kiremt* (the main rainy season from June to September), *Bega* (the long dry season from October to February) and *Belg* (the short rainy season from March to May). *Kiremt* is the most important season, as it accounts for about three quarters of total annual rainfall and for most of the cropping activities for the rain-fed agriculture of the country.

The southwestern part of Ethiopia is the wettest place in the country (Fig. 2.10a). The low lying areas in the southeast and northeast parts of the country are characterized by their high temperatures (Fig. 2.10b). The hottest place on earth, the Danakil Depression, is located in the northeastern part of the country.



(a)



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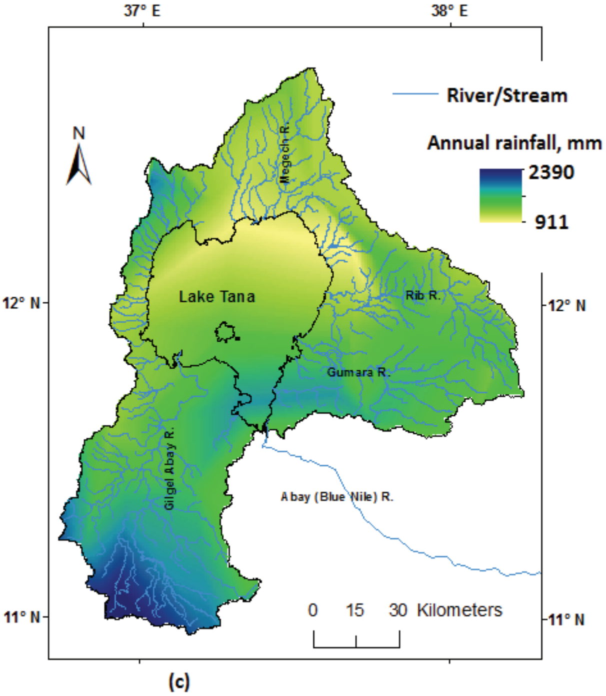

Figure 2.10: Mean annual climatic variables (a) rainfall, (b) temperature over Ethiopia (source: Engida, 2010) and (c) annual rainfall over Lake Tana basin (based on 2012 and 2013 years data), derived from the point input rainfall data of 33 stations in the basin (data for the years 2012 and 2013) and by building triangular irregular networks (TIN) using the arc GIS 10.1 tool by the Delaunay triangulation method of interpolation.

Based on the rainfall data of available stations within and around the basin (Fig. 2.11), the mean annual rainfall of the Lake Tana basin was estimated as 1345 mm (Engida, 2010). Generally, the upper southern part of the Lake Tana basin (upper part of Gilgel Abay catchment) receives high amount of rainfall (can reach 2400 mm in a year, Fig. 2.10c). On the contrary, the northern portion in the vicinity of the lake gets the minimum amount of rainfall (as low as 910 mm/year). Like other parts of Ethiopia, rainfall is highly seasonal in the basin and more than 70% of the annual rainfall occurs in the rainy season (*Kiremt*).

The mean annual temperature is about 20°C and in some pocket areas (the most upper eastern and southern parts of the basin) the mean annual temperature can drop as low as

12°C. According to the Köppen climate classification system, the basin has a warm temperate climate with wet summer.

2.4.2 Meteorological data

The National Meteorological Agency of Ethiopia (NMA) is the major source of meteorological data in the country. There are more than thirty meteorological observation stations in the basin (Fig. 2.11). The stations at Bahir Dar, Adet, Dangila, Debretabor, Gondar and Aykel are the principal meteorological stations, meaning several climatological variables such as rainfall, maximum and minimum temperatures, sunshine hour, relative humidity, wind speed at 2 m and 10 m heights and pitch evaporation are measured. The other stations measure only a few variables, e.g. only minimum and maximum air temperatures of the day and total rainfall amount in 24 hours or only total daily rainfall. Few of the stations like Bahir Dar and Gondar are equipped with floating-type recording gauges for rainfall measurements at shorter time scales, while most of the stations use manual rain gauges for rainfall recording.

2.4.3 Hydrometric stations and data acquisition

There are a number of hydrometric stations in and around the basin owned by Hydrological Department of the Ministry of Water, Irrigation & Energy of Ethiopia, making the area for which discharge data is available in the Tana basin to be about 42% of the total basin area draining towards the lake (SMEC, 2008). Currently, almost all the hydrometric stations use the staff gauge to record the water levels twice a day manually. About 40% of the stations have the housing for the automatic water level recorders, but these recorders were all removed around the late 1980's, except for the key station on the Abbay at Bahir Dar (SMEC, 2008).

The twice daily readings are clearly insufficient to estimate daily discharges as there are high chances for the peak floods to pass unobserved, especially in smaller rivers where rising and falling limbs of the hydrographs are often very swift. Installation of water level recorders is essential for streams where the level is subject to abrupt fluctuations. Moreover, a large number of the stations have been victims of siltation, bank overflow and unstable cross-sections (SMEC, 2008). Hence, it was necessary to improve the reliability of the hydrological data (mainly discharge and sediment data) in the basin for a better understanding of its hydrology. Accordingly, 17 new hydrometric stations were established in the basin (Fig. 2.11) to monitor water level and sediment of the major rivers for this study. This has increased the coverage of gauged area of the basin to 60%. Six of the stations (three upstream just at the edge of the floodplain and another three downstream within the floodplain) were mainly set to study the floodplain hydrology in the basin (Chapters 3 and 5).

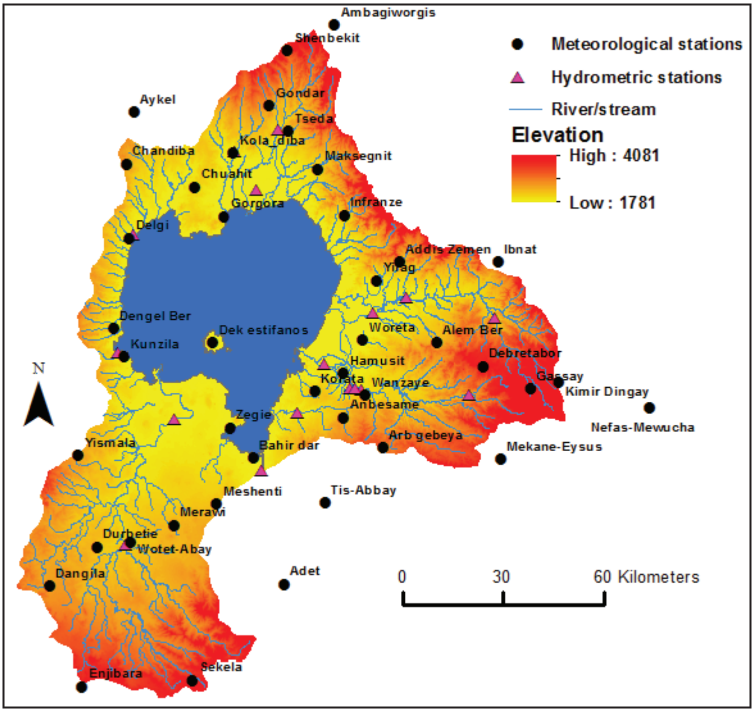

Figure 2.11: Meteorological and hydrometric stations within and nearby the Lake Tana basin (Hydrometric stations shown here were established for this research)

Water level measurements have been made using automatic water level recorders (every 10 or 20 minutes) and manual readings from a staff gauge (three times a day, at about 7 am, 1 pm and 6 pm) to calibrate the automatic pressure transducers. The automatic water level recorder (or Mini-Diver®) has a pressure sensor to determine water level and a temperature sensor (Fig. 2.12). It can be set to any desired time interval and the data are retrieved by inserting the Mini-Diver in a USB reading unit connected to a laptop or PC with Diver-Office. For each measurement, the date, time, water level and temperature are stored.

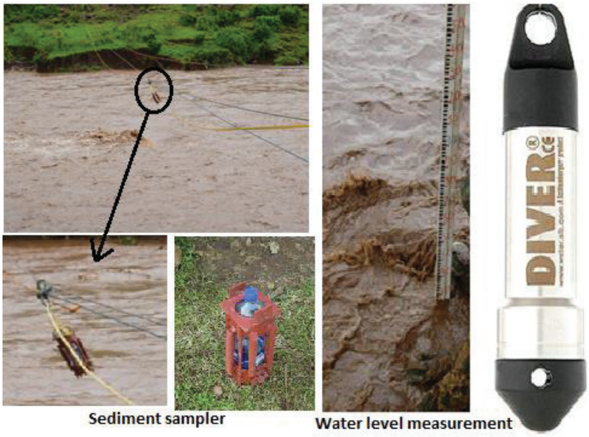

Figure 2.12: Details of a typical monitoring station installation

The installation of the monitoring stations involved the construction of pillars on left and right banks, erecting staff gauges and placing the diver on the bed of the river. The diver can be placed using different techniques depending on the site condition, for example at Wanzaye Station it has been placed inside a pipe bottom, which is erected at one side of the river bank with holes on the surface to allow entry of water to the pipe (Fig. 2.12). The same pipe has also been used as a staff gauge for the manual readings. A Diver® (with accuracy of 5 cm) measures the water level based on a highly accurate pressure sensor that measures an absolute pressure. This pressure is then related to the height of the water column above the measuring instrument and the prevailing air pressure. A Baro-Diver® was used to record atmospheric pressure.

Flow velocity measurements were taken using the float method (surface velocity), owing to the difficult site conditions to use a current meter during floods, but also velocity measurements were made using a current meter at different flow depths during low flows for some of the rivers. A relationship was developed between the two types of measurements (Fig. 2.13) to convert surface flow velocities to mean flow velocity. From this relationship, a factor of 0.86 was found which is in agreement with the recommendation stated in Chow (1959) when the ratio of the immersed depth of float to depth of water is 0.10 or less. The diver readings have been calibrated using the staff gauge readings for each station and the correlation coefficient R^2 varied from 0.81 to 0.98 (Fig. 2.14). For some stations (those that were not easily accessible during the rainy season), the staff gauge readings were not found trustworthy. These stations were minimally supervised as compared to others because of accessibility problems in the rainy season and the staff recorders failed in recording the readings at the exact time. In such circumstances, water level measurements by the automatic recorders were trusted with corrections applied from other well managed sites.

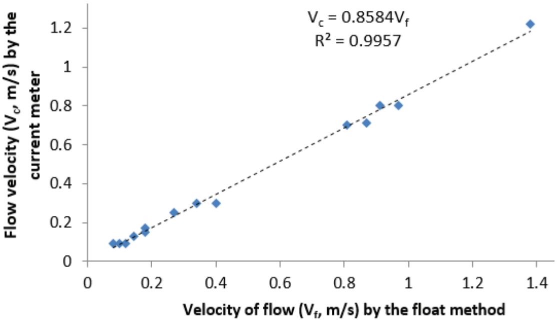

Figure 2.13: Flow velocity correlations between current meter and float methods of flow velocity measurement at four rivers in the Lake Tana basin

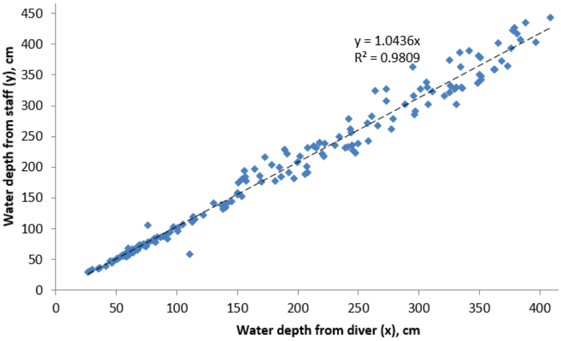

Figure 2.14: Comparison of water level measurements from a staff gauge and an automatic recorder (diver) for a well-managed station at a bridge along the Rib River.

Besides the flow velocities, survey of the cross-sections of the river channels were necessary to prepare the rating curves (plots of discharge versus stage for a given point on a stream). Measurement of river cross-section and the longitudinal slope were made using surveying equipment (total station). Fig. 2.15 depicts the cross-sections for one of the stations (Wanzaye station on Gumara River). Depending on the condition of the rivers at measurement stations, cross-sections were updated (e.g. when there was excessive bank erosions, river bed changes).

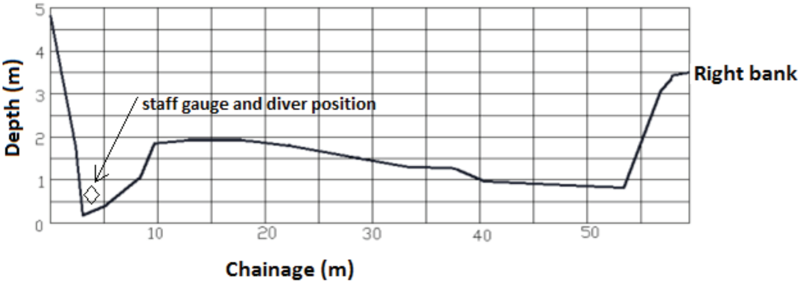

Figure 2.15: River cross-section at Wanzaye Station

Once the automatic water level recorders were calibrated from the staff gauge readings, the variability of the average daily discharge estimates obtained from staff gauges (conventionally used method in the basin) of three times a day water level readings and automatic water level recorders of fine time resolution (every 10 or 20 minutes record) were evaluated for bigger and smaller catchments to assess the reliability of staff gauges monitored twice a day (Fig. 2.16 and Fig. 2.17). The results indicate better correlations between the two types of measurements for bigger than smaller catchments. This is because in smaller catchments, floods occur very rapidly and last for shorter periods. Therefore they can easily pass unattended by the recorders. Hence, staff gauges are better used for bigger catchments than smaller catchments if the frequency of monitoring is small (say twice or three times a day) and there are no automatic water level recorders. After calibrating the divers, the data of the staff gauges were not used in this study. The automatic water level data were used as the recordings are based on very fine time resolution (water level recording time set to be as low as 10 minutes).

The Lake Tana level has been monitored at three stations (since 1959 at Bahir Dar station, one of three stations) by the Hydrological Department of the Ministry of Water, Irrigation & Energy of Ethiopia. Based on the long term lake level data at Bahir Dar station, the average annual lake level fluctuation before regulation was found to be 1.6 m. Bathymetric surveys of Lake Tana, conducted at four different times, i.e. in 1940 (Morandini, 1940), 1990 (Pietrangeli, 1990), 2006 (Kaba, 2007) and 2012 by Omega Development Service Plc, have been used to establish relationships between water level-area-volume of the lake during the lake water balance and lake management studies (Chapters 5 and 6).

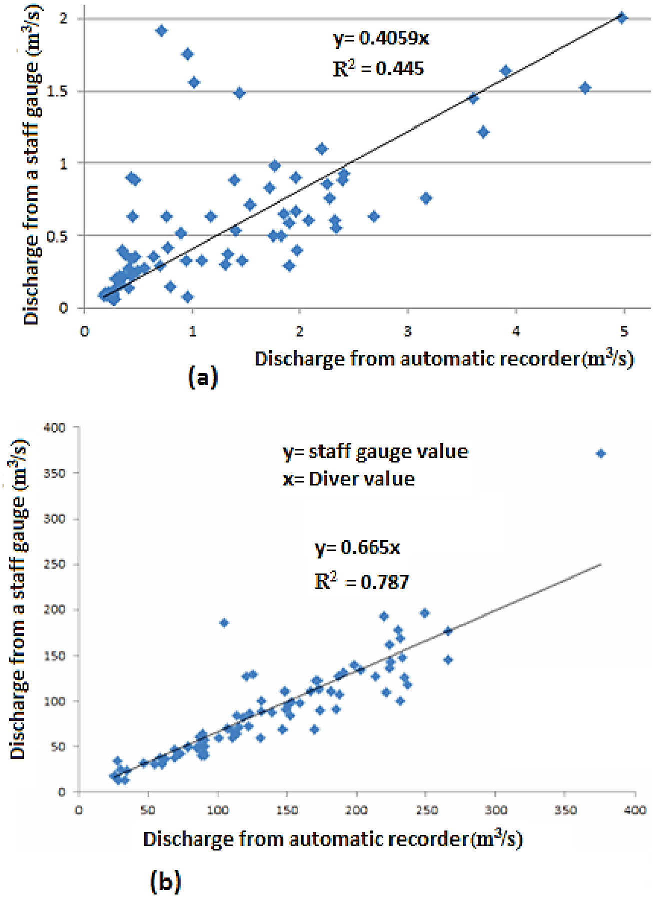

Figure 2.16: Relation of mean daily discharges obtained from staff gauges (three times a day) and divers (every 5 or 10 minutes) water level readings at (a) Kizin Station, tributary to Gumara River (catchment area at the station is 8.4 km^2) and (b)Wanzaye Station for Gumara River (catchment area at this station is 1236 km^2)

CHAPTER 3

3. Effects of the floodplain on river discharges and variability of runoff in the basin[1]

Abstract

This chapter presents a study on an extensive floodplain adjacent to Lake Tana (Ethiopia) and its lowland tributaries, to enhance our understanding of the water of the lake and to better manage the natural resources in the floodplain. Variability of runoff in the basin has also been assessed. Discharge measurements made at 12 stations were used for this purpose. The effects of the floodplain on river discharges were investigated using the upstream and downstream discharge observations of the Gumara, Rib and Megech Rivers. The total annual runoff coefficients ranged between 0.23 and 0.81 in 2012 in the basin. Discharge varied depending on drainage density ($r = 0.75$), lithology ($r = -0.72$ for percentage of Tertiary igneous rocks) and land use/land cover conditions ($r = 0.61$ for dominantly cultivated land with no significant other land use types). Analyses revealed that the floodplain abstracted 809 mm of water with a corresponding increase in floodplain storage of 992 mm during the beginning of the rainy season (June to July) and released stored water starting from August until the middle of September. However, the annual water balance indicated that the runoff contribution from the Rib and Megech floodplains is negligible. But the floodplain downstream of the Gumara River showed a considerable runoff contribution to the river, also in relation to the presence of springs. The floodplain acts as storage of flood water, and consequently the magnitude of peak floods was on average 71 m^3/s smaller downstream than upstream in the floodplain.

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[1] Adapted from Journal of Hydrology
Dessie, M., Verhoest, N.E.C., Admasu, T., Pauwels, V.R.N., Poesen, J., Adgo, E., Deckers, J., Nyssen, J., 2014. Effects of the floodplain on river discharge into Lake Tana (Ethiopia). Journal of Hydrology 519: 699-710. doi: 10.1016/j.jhydrol.2014.08.007.

3.1 Introduction

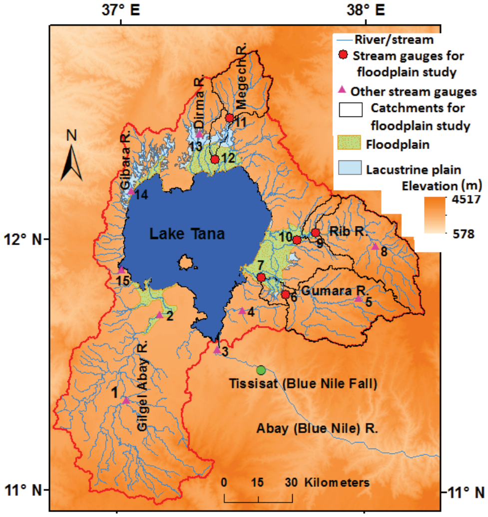
Many diverse natural functions and services can be attributed to floodplains such as providing fish and wildlife habitat, supporting natural vegetation, buffering peak floods (Prach et al., 1996; Kingsford, 2000): hence they are vital landscape elements. Moreover, they are areas of intense human activities. The repeated erosion and deposition of sediments, inundations during overbank floods, and complex groundwater-surface water exchange processes make floodplains dynamic systems (Tochner et al., 2008). They have a major impact on the transfer of water and sediments from upland catchments through river systems to the lakes or seas (Dunne et al., 1998; Hamilton et al., 2002; Meade et al., 1985). Hydrological processes and inundations in the floodplain have remained important areas of research to understand the ecology of floodplains and interactions with associated river-floodplain systems (Hughes, 1980; Richey et al., 1989; Coe, 2000; Loveless et al., 2000).

Lake Tana, in the northwestern highlands of Ethiopia, is associated with an extensive floodplain adjacent to the lake and its lowland tributaries. The floodplain is the hydrological connector between the lake and the upper catchments, and affects the water balance and sediment flux of the lake. Given the importance of the lake with respect to different water resource development projects, fishery, biodiversity, transport and tourism, several studies have been made to understand its water balance (Kebede et al., 2006; 2011; SMEC, 2007; Chebud and Melese, 2009; Wale et al., 2009). Kebede et al. (2011) estimated the runoff contributions from the floodplains using an isotopic hydrological approach. They demonstrated that the waters in the floodplains originate from local rainfall and river overflows and that there is nearly no linkage between the surface waters in the floodplains and the shallow groundwater in alluvio-lacustrine sediments, suggesting that after the rainy season the floodwater disappears by evapotranspiration or surface drainage rather than seepage to the subsurface. Studies by Kebede et al. (2006), Wale et al. (2009) and Chebud and Melese (2009) did not differentiate between the upper ungauged catchments and the floodplain when estimating the runoff contributions from the ungauged catchments including the floodplain. However, floodplains are considered as specific ecosystems, oscillating between terrestrial and aquatic phases (Junk, 1996), having different topography, soils and vegetation patterns. Due to difficulties in acquiring data for the floodplain, hydrological processes in the Lake Tana basin floodplain remain poorly understood. This has limited a more accurate determination of the lake water balance and the understanding of the ecosystem. The objective of this chapter is to better understand the effects of the floodplain on the discharge of the rivers draining the hillslopes (upstream reaches) and to understand the hydrological behavior (river and floodplain interactions) by measuring discharges at the foot of the hillslopes, at the interface of the floodplain (upstream stations), and within the floodplain (downstream stations). Moreover, variability of runoff in the basin is investigated and explanatory factors are suggested.

3.2 Materials and methods

3.2.1 Water level measurements and discharge rating curves

This study involves field measurements of river flow stages at gauging stations along main river courses, upstream just at the edge of the floodplain and downstream within the floodplain, to enable the computation of flow discharges and study the floodplain hydrology (Fig. 3.1).



Details of numbers shown in the figure

Number	Name of stream gauge	Name of catchment
1	Picolo	Gilgel Abay
2	Chimba	Gilgel Abay
3	Bahir Dar	Tana
4	Gelda	Gelda
5	Gumara	Gumara
6	Wanzaye	Gumara
7	Lower Gumara	Gumara
8	Rib near dam	Rib
9	Rib at Abobahir	Rib
10	Rib at bridge	Rib
11	Megech at bridge	Megech
12	Lower Megech	Megech
13	Dirma	Dirma
14	Gibara	Gibara
15	Kunzila	Tana Beles outlet

Figure 3.1: Stream gauges, the floodplain and catchments used for the floodplain study in Lake Tana basin; topographic data from SRTM DEM

Other gauging stations were also installed to study the characteristics of hilly catchments with respect to runoff (Fig. 3.1). The location of the upstream stations is chosen in such a way that no overbank flow prevails near these stations during any flow condition and the measurements capture all the upstream flows during peak discharge. Likewise, stations in the floodplain have been set at locations with minimum possible bank overtopping, but overtopping can still take place upstream of these stations. The rating curves of the stations in the floodplain might be inaccurate as a result of backwater effects (if any) during high lake levels. However, we could not consider this effect in current study due to lack of data.

River flow level measurements have been made using Mini-Divers, automatic water level recorders (every 10 minutes), and manual readings from staff gauges (three times a day, at about 7 AM, 1 PM and 6 PM) between December 2011 and December 2012 (Fig. 3.2).

Figure 3.2: Typical monitoring station installation with staff gauges (vertical poles) and a pipe containing a Mini-Diver, at the deepest point of the river cross-section (Lower Gumara station, March 2012).

Since continuous measurements of discharge are usually not feasible, records of discharge were computed from the relationship between stages and discharge (rating curve). The rating curves (Fig. 3.3) were produced after the survey of the cross-sections of the river channels (Fig. 2.15) and the measurement of flow velocity at different flow stages.

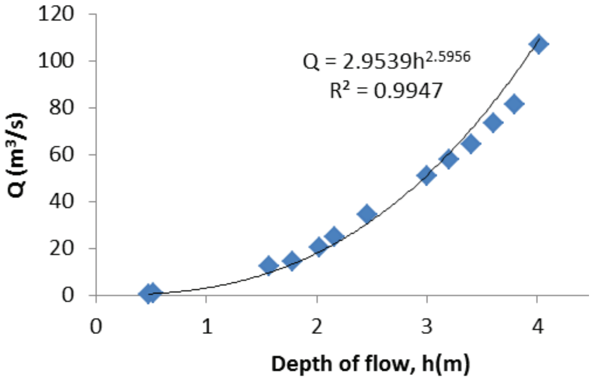


Figure 3.3: A typical flow depth-river discharge (Q) rating curve for the Rib River at the downstream bridge station.

If Q (m^3/s) and h (m) are discharge and water level respectively, then the relationship is expressed as

$$Q = a\,h^b \tag{3.1}$$

where a and b are fitting coefficients (Table 3.1). The coefficient b was often quite high, which is largely explained by the shape of the cross-sections. The value of coefficient b for rectangular and triangular shapes is about 1.5 and 2.5 respectively, and for relatively deep narrow rivers, the exponent will commonly be greater than 2 and sometimes exceed a value of 3 (Herschy, 1993). Most of the river cross-sections in this study are characterized by irregular shapes and deeper profiles, leading to relatively higher values of coefficient b.

3.2.2 Rainfall distribution

Point measurements of precipitation were collected from the National Meteorological Agency of Ethiopia (NMA) for 34 stations in the basin (Fig. 2.11). Several techniques have been applied to compute areal rainfall depth for each catchment of interest: Thiessen polygon, Inverse Squared Distance Weighting (IDW) and Satellite derived Rainfall Estimates (RFEs), obtained from the National Oceanic and Atmospheric Administration Climate Prediction Center (NOAA-CPC):http://www.cpc.ncep.noaa.gov/products/fews/. The purpose is to compare the areal rainfall estimates of the three methods and assess the reliability of RFEs, obtained from of NOAA-CPC.

Table 3.1: Rating curve coefficients a and b (eq. 3.1) for the measuring stations on the studied rivers. The coefficients for some stations have been updated and differ from those reported in Dessie et al. (2014) after additional data were collected and due to changes on cross-sections.

Measurement station	**a**	**b**	**R^2**
Gilgel Abay (Picolo)	70.4	2.10	0.985
Gilgel Abay (Chimba)	10.44	2.21	0.952
Gelda	4.74	2.64	0.953
Gumara (Wanzaye)	44.1	1.97	0.994
Lower Gumara	1.55	3.16	0.943
Rib near Dam	24.63	2.32	0.940
Rib at Abobahir	4.4	2.49	0.993
Rib at bridge	2.95	2.60	0.995
Megech at bridge	36.42	2.64	0.981
Lower Megech	5.29	2.59	0.974
Dirma	7.95	2.58	0.958
Gibara	10.36	2.00	0.943

The daily rainfall of the 34 meteorological stations (2006-2012 years data) and decadal data of the RFEs from NOAA were summed to monthly data for each corresponding year without missing meteorological data. Following the method developed by Jacob et al. (2013), the meteorological stations data were assigned to specific RFE pixels by projecting the location of the rainfall station into the Albers equal area conic projection (Clarke 1866 spheroid) used for the RFEs. Only rainfall from April to September, which accounts for 95% of the total yearly rainfall (2006-2012), was used to calibrate the RFE images. Studies by Beyene and Meissner (2010) and Jacob et al. (2013) show that RFE images are less accurate in measuring rainfall in the dry season (from October to February).

The resulting rainfall estimates of NOAA have been calibrated against the observed values (Fig. 3.4), and the 2012 areal rainfall estimates were computed using the regression equation of the calibration.

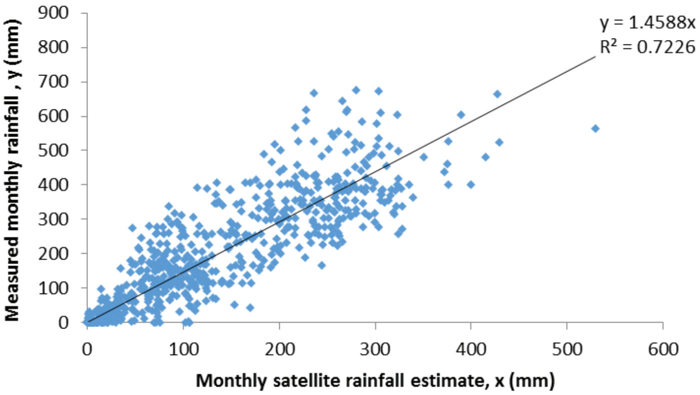


Figure 3.4: Measured and satellite estimated rainfall correlation for monthly rainfall data (April-September) for the period 2006-2012.

3.2.3 Runoff coefficients and river discharges

Using the rating curves developed for each station, the measured water depths were converted into flow discharges whereby monthly and annual runoff at each station was computed. The total annual runoff coefficient (TARC) was calculated by dividing the total annual runoff depth by the total annual rainfall depth in each catchment undertaken by the measurement stations. Similarly, monthly and sometimes weekly runoff coefficients were computed. The TARCs were used to study the spatial and temporal variability of runoff. Water balance studies and analysis of measured discharge at upstream and downstream stations were carried out to investigate the effect of the floodplain on river discharges.

3.2.4 Catchment characteristics and floodplain mapping

Catchment characteristics (Table 3.2) and floodplain mapping were made using different sources and own field data. Topographical features like catchment delineation, slope, and stream length were determined using the Digital Elevation Model (DEM) from the Advanced Space borne Thermal Emission and Reflection (ASTER) with a 30 m ground resolution (http://earthexplorer.usgs.gov/). Previous mapping studies (SMEC, 2007;

Poppe et al., 2013), combined with own additional field data and GPS survey were used to delimit the floodplain (Fig. 3.1).

The Ministry of Water Resources and Energy (GIS & RS Section, Addis Ababa) provided geological and land use maps of the study area (unpublished). The geomorphological map of the basin (Poppe et al., 2013) was also used.

To assess the impact of vegetation on the runoff, Normalized Difference Vegetation Index (NDVI) values were calculated from Landsat 4-5 Thematic Mapper image data, acquired from the USGS Global Visualization Viewer with a resolution of 30 m (for September and January 2011 to represent high and low vegetated periods in the year), as

$$NDVI = \frac{NIR - VIS}{NIR + VIS} \qquad (3.2)$$

where VIS and NIR stand for the spectral reflectance measurements acquired in the visible (red) and near-infrared regions, respectively.

3.2.5 Evapotranspiration

For the water balance investigations, the potential evapotranspiration (ET) was computed using the FAO Penman-Monteith method (Allen et al., 1998) and the climatic data of year 2012 were used from meteorological stations of Bahir Dar, Woreta, Addis Zemen and Gorgora (Fig. 2.11). However, the four stations may not be representative of the whole study area to compute the mean areal values of potential evapotranspiration, owing to the large extent of altitudinal range in the study area. Yet, they are the only stations available with temperature data close to the floodplain and the incremental areas. Data like humidity, sunshine hours and wind speed were solely taken from Bahir Dar station.

Table 3.2 : Characteristics of catchments outside the floodplain

Catchment characteristics		Catchments								
		Gumara (Wanzaye)	Rib near dam	Rib at Abobahir incremental**	Gilgel Abay (Picolo)	Chimba incremental***	Megech at bridge	Gelda	Dirma	Gibara
Topography	Average slope gradient (%)	18.0	16.4	16.7	11.5	5.2	21.0	7.7	9.8	6.0
	Total stream length (m)	398058	94948	243283	523406	600090	157300	66011	51171	7432
	Drainage density (m/km^2)	322.2	285.6	289.2	315.4	309.5	306.2	304.6	314.7	319.0
	Hypsometric integral	0.46	0.48	0.29	0.48	0.17	0.50	0.47	0.46	0.50
	Length of longest flow path (km)	66.5	42.0	55.0	67.4	88.0	38.8	29.0	27.2	11.6
	Area of level land (%)*	23.9	24.0	38.1	53.7	82.8	17.6	68.0	48.4	76.0
	Area of hilly land (%)	59.7	64.4	44.2	38.3	16.3	59.1	31.2	50.0	24.0
	Area of steep land (%)	16.4	11.6	17.7	8.0	0.9	23.3	0.9	1.6	0.0
Lithology	Area with alluvium or colluvium (%)	0.0	0.0	11.8	1.4	9.4	0.6	0.0	0.0	0.0
	Lacustrine / marshy areas (%)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	30.2	45.4
	Area with Quaternary igneous rock (%)	0.9	0.0	0.0	65.6	87.0	0.0	5.9	0.0	1.9
	Area with Tertiary igneous rock (%)	99.1	100.0	88.2	33.0	3.6	99.4	94.1	69.8	52.7
Land use	Area dominantly cultivated with no significant other land use types (%)	37.3	0.5	0.8	51.8	37.0	1.0	68.0	0.0	0.0
	Area dominantly cultivated with additional grassland, shrubs and other (%)	28.9	62.8	56.7	6.9	28.6	88.7	0.0	100.0	97.5
	Area moderately cultivated, mixed with grassland and shrubs (%)	25.3	18.1	26.1	41.1	32.4	10.3	22.0	0.0	2.5
	Area moderately cultivated, mixed with grassland only (%)	8.6	18.6	17.2	0.2	2.0	0.0	0.0	0.0	0.0
NDVI	Sept. 2011	0.44	0.42	0.4	0.48	0.49	0.28	0.44	0.33	0.32
	Jan. 2011	0.13	0.12	0.09	0.18	0.14	0.12	0.1	0.13	0.09

* Catchment is taken as level when its average slope gradient is <= 8%, hilly when 8% < slope gradient <= 30% and steep when slope gradient > 30%.
** Rib Abobahir incremental is the catchment between the upstream station (Rib near dam) and the Abobahir Station (downstream).
*** Chimba incremental is the catchment between Gilgel Abay Picolo Station (upstream) and Gilgel Abay Chimba Station (downstream station).

3.3 Results and discussion

3.3.1 Areal rainfall estimates

The NOAA estimates shown on Table 3.3 are after rescaling of the correlation results (Fig. 3.4). Even after rescaling, the NOAA method underestimates the rainfall values (Dinku et al., 2007; Jacob et al., 2013). On the other hand, the Thiessen polygon method has resulted in relatively higher areal rainfall estimates. However, the fundamental principles of applying this technique may produce inaccurate results because of the effects of topographical variation within the basin that are not accounted for and due to the limited number of available rainfall stations. The same is valid for the IDW method.

Table 3.3: Annual rainfall depth estimates for the studied catchments using different methods

Catchment	Catchment area (km^2)	Estimated annual rainfall depth (mm)		
		Thiessen polygon method	IDW Method[1]	NOAA estimate[2]
Gumara (Wanzaye)	1236	1407	1395	1320
Lower Gumara	1351	1402	1393	1335
Rib near dam	332	1420	1396	1205
Rib at Abobahir	1174	1414	1370	1185
Rib at bridge	1308	1428	1378	1152
Gilgel Abay (Picolo)	1660	1887	1761	1604
Gilgel Abay (Chimba)	3598	1706	1645	1564
Megech at bridge	514	1225	1220	1150
Lower Megech	631	1202	1203	1251
Gelda	217	1587	1493	1360
Dirma	163	1110	1160	1291
Gibara	23	1997	1436	1551

[1] based on Inverse Distance Squared Weighing (IDW)

[2] based on Satellite derived rainfall estimates obtained from the National Oceanic and Atmospheric Administration Climate Prediction Center (NOAA-CPC)

The areal rainfall estimates by the IDW technique are adopted in this chapter as the estimates are in between those of the two other methods. A similar method has also been used by Wale et al. (2009) in estimating runoff contributions from ungauged catchments in the Lake Tana basin. Although we are aware of the shortcoming of not accounting for topography, we were obliged to restrict ourselves to the chosen set of techniques, as the low number of measurement stations in the sub-catchments did not allow to properly incorporate the relationship between elevation and observed rainfall into the interpolation. In fact, the correlation of annual rainfall with topography for the basin was poor, as shown by the scatter plot of the 2012 annual rainfall and corresponding elevation of the 32 stations in the basin (Fig. 3.5).

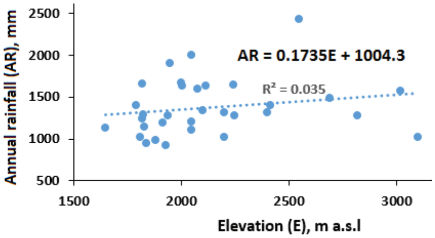


Figure 3.5: Plot of the 2012 annual rainfall and elevation of the 32 rainfall stations in and around the Lake Tana basin

3.3.2 Spatial variability of runoff in the basin

The total annual runoff coefficients (TARCs) vary between 0.23 and 0.81 (Fig. 3.6), with an average of 0.5 in the basin for the year 2012. This value is larger than an average runoff coefficient of 0.23 obtained for the catchment of Geba River, a sub-catchment of Tekeze basin (Zenebe et al., 2013). Runoff coefficients as high as 0.6 have also been reported in the Blue Nile basin, and TARCs in the Blue Nile basin are larger than in the Tekeze, Awash and Wabe Shebele basins (Fig. 2.8) (Nyssen et al., 2004). This is attributed to the smaller amount of rainfall and high evapotranspiration in the Tekeze, Awash and Wabe Shebele basins since they are mainly situated in dry sub-humid to arid regions (Engida, 2000).

Despite the comparable annual rainfall amounts with Gumara, Gelda and Gibara, the TARC for the Rib sub-catchment is exceptionally small (Fig. 3.6). The possible explanation can be illustrated using a simplified annual water balance.

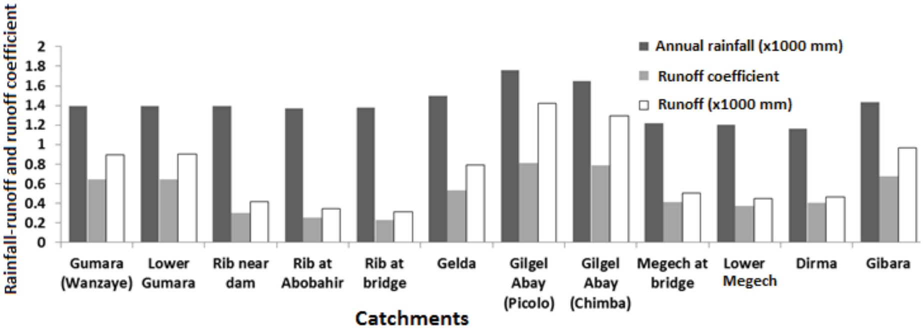


Figure 3.6: Annual rainfall, runoff (mm) and runoff coefficient for the studied catchments in the Lake Tana basin. Refer to Fig 3.1 for location of stations.

On an annual basis for a closed basin assuming no change in storage from year to year and assuming that there is no flow under the gauge (i.e., flow out of the control volume)

$$ET_A = P_A - R_A \quad (3.3)$$

where ET_A is the annual evapotranspiration (mm/year), P_A is the annual precipitation (mm/year) and R_A is the annual discharge (runoff in mm/year), and

$$TARC = R_A / P_A \quad (3.4)$$

where TARC is the total annual runoff coefficient as defined in Section 3.2.3.

This can be rewritten with the yearly mass balance as

$$TARC = (P_A - ET_A) / P_A = 1 - ET_A/P_A \quad (3.5)$$

This last equation shows that the total annual runoff coefficient depends on the evapotranspiration in the basin and on the precipitation.

Therefore, the exceptionally smaller TARC in Rib sub-catchment can be because of either high evapotranspiration and/or a discharge of groundwater that is not captured by the gauge measurements (as it discharges downstream of the gauges). Given the poor rainfall station density, an overestimation of the areal rainfall in the sub-catchment can also reduce the TARC owing to the mountainous nature of the area and high orographic rainfall variations.

Climatic variables (like temperature, wind speed, relative humidity, etc.) have important roles in affecting evapotranspiration. Monthly potential evapotranspiration estimation results (Table 3.4) using relevant climatic data show that the highest average monthly evapotranspiration rates in 2012 for the floodplain and incremental areas were 6.12

mm/day and 5.79 mm/day respectively, which were both observed in the Rib catchment and in the month of April. The daily potential evapotranspiration estimates show slight variations such that the highest daily evapotranspiration rates for the floodplain and incremental areas were 6.7 mm/day (on 25th of March) and 6.4 mm/day (on 6th of May) respectively, both observed in Megech catchment (Fig. 3.7). However, appreciable evapotranspiration variations (Table 3.4) were not noticed between the Rib and its adjacent catchments (Gumara and Megech).

Evapotranspiration is also much related to catchment properties and therefore the variability in TARCs can be due to variation in catchment properties besides the climatic factors (Nyssen et al., 2004).

Table 3.4: Average monthly potential evapotranspiration (ET_m) for the incremental areas and floodplain

Month	ET_m (mm/day) for incremental area* in			ET_m (mm/day) for the floodplain in		
	Gumara	Rib	Megech	Gumara	Rib	Megech
January	4.33	4.37	4.32	4.49	4.50	4.52
February	5.12	5.20	5.17	5.56	5.55	5.57
March	5.46	5.57	5.57	5.89	5.87	5.88
April	5.73	5.78	5.74	6.09	6.12	6.08
May	5.32	5.36	5.31	5.56	5.55	5.56
June	4.41	4.41	4.39	4.73	4.73	4.74
July	3.40	3.40	3.37	3.47	3.47	3.48
August	3.37	3.35	3.36	3.50	3.51	3.51
September	3.78	3.77	3.79	3.91	3.92	3.92
October	4.43	4.48	4.44	4.49	4.49	4.50
November	3.95	3.98	3.97	4.12	4.13	4.14
December	4.01	4.00	4.03	4.02	4.04	4.05

*incremental area is the catchment area between the upstream and downstream stations

Explanatory factors for discharge from the different catchments were assessed for 9 hilly catchments using correlation analyses (Table 3.5). A preliminary analysis showed that there is no correlation between the explanatory factors themselves. The three catchments that lie partly in the lacustrine plain are not incorporated in this analysis as they are expected to behave differently from those draining the hills. The effect of the lacustrine plain will also be dealt with further in this chapter.

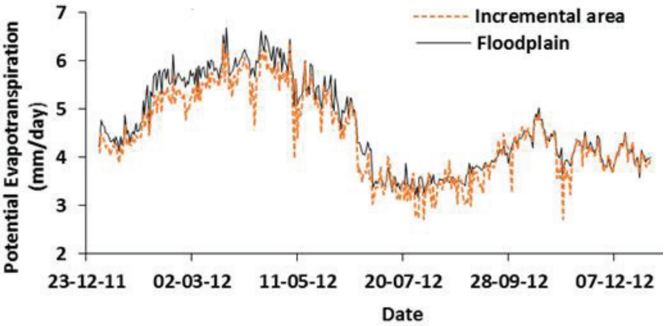


Figure 3.7: Daily potential evapotranspiration estimates of the floodplain and incremental area for Megech River.

The highest runoff values were observed in the Gilgel Abay catchment (0.81), in line with the findings of SMEC (2007). The higher values of TARC in the Gilgel Abay catchment are likely related to the higher rainfall in its catchment (may induce quick soil saturation). This is substantiated by the strong correlation coefficient (r = 0.92) between annual rainfall at catchment level and TARC (Table 3.5). As explained above, uncertainties on the estimation of the catchment precipitation remain, in relation to poor station density whereas there is large spatial variability of rain in the Blue Nile basin (Conway and Hulme, 1993). If the Thiessen polygon method of areal estimate of precipitation for the catchment is considered, the TARC reduces to 0.75. However, the TARC is still very high and hence it is very uncertain and it should be treated with care. Moreover, uncertainties on the discharges cannot be ruled out, particularly in relation to flow velocity determination as it was measured using the float method. SMEC (2007) argues that the higher runoff in Gilgel Abay catchment at Picolo measurement station is due to its larger sub-surface catchment than the surface water catchment. Considering these higher uncertainties, the runoff coefficient for Gilgel Abay at Picolo Station was not used for further analysis in the subsequent chapters of this dissertation.

In the hilly catchments, runoff coefficients further showed good correlations with drainage density (r = 0.75) (Table 3.5). The importance of drainage density as a quantitative measure of a river system in a drainage basin and its role in affecting runoff has been noted by numerous investigators (e.g. Horton, 1945; Strahler, 1957; Patton and Baker, 1976). It is a measure of basin efficiency to remove excess precipitation inputs, and its relatively smaller value in Rib catchment (Table 3.2) is the likely reason for the lower drainage efficiency and its smaller overland flow generation. The rainfall cannot easily drain to the river and is subjected more to either infiltration (deep percolation) or evaporation. Low values of drainage density are commonly associated with high permeability of bedrock (Horton, 1945; Carlston, 1963). In the case of Rib River, its catchment is underlain by Tertiary Termaber basalts which commonly include large amounts of tuffs (Merla et al., 1979) which may be very permeable. The Rib River is the only one, among the studied rivers, to be totally underlain by the Termaber basalts.

The role of land use in affecting the runoff in the basin has also been assessed. The land use data collected from Ministry of Water Resources and Energy (GIS & RS Section, Addis Ababa) shows that the major land cover types are dominantly cultivated land (45%), moderately cultivated land (32%), water (18%), grassland (2.5%), shrubs (2.2%) and others like urban, forest and plantations constitute 0.3%. The cultivated lands are usually mixed with other types of land uses and the proportions for the different catchments are shown in Table 3.2. The proportion of the catchments occupied by hills fairly affects the runoff. Hills and moderately cultivated land (including grass land) seem to reduce runoff volume, and dominantly cultivated land with no significant other classes affected runoff volume positively. An explanation can be found in the fact that soil and water conservation works are being undertaken in Ethiopia (Osman and Sauerborn, 2001), particularly in hilly areas where stone bunds and terraces are common (Fig. 2.7). These catchment management interventions increase infiltration (possibly also deep percolation) and reduce runoff (Nyssen et al., 2010). Level land of the catchments is mostly clayey and often saturated, causing higher runoff rates, whereas hilly land is very stony and contributes to infiltration (Bayabil et al., 2010).

Table 3.5: Pearson correlations of catchment characteristics and runoff variables

Catchment characteristics (n =9)		Hydrological variables and Pearson correlation coefficient (r)		
		Annual runoff (m^3)	Annual runoff depth** (mm)	Total annual runoff coefficient (TARC)
		r	r	r
Topography	Catchment area (km^2)	0.95*	0.64*	0.57
	Average slope gradient (%)	-0.23	-0.53	-0.54
	Drainage density (m/km^2)	0.33	0.63*	0.75*
	Hypsometric integral	-0.46	-0.12	-0.09
	Length of longest flow path (km)	0.85*	0.44	0.37
	Area of level land (%)	0.31	0.58	0.59
	Area of hilly land (%)	-0.38	-0.6*	-0.6*
	Area of steep land (%)	-0.12	-0.43	-0.46
Lithology	Area with alluvium or colluvium (%)	0.31	-0.06	-0.13
	Lacustrine / marshy (%)	-0.41	-0.01	0.1
	Area with Quaternary igneous rock (%)	0.92*	0.78*	0.71*
	Area with Tertiary igneous rock (%)	-0.74*	-0.74*	-0.72*
Land use	Area dominantly cultivated with no significant other classes	0.56	0.66*	0.61*
	Area dominantly cultivated with grass land, shrubs and other	-0.62*	-0.56	-0.46
	Area moderately cultivated, mixed with grass land and shrubs	0.8*	0.56	0.41
	Area moderately cultivated, mixed with grass land only	0.22	-0.54	-0.63*
NDVI	Sept. 2011	0.73*	0.56	0.45
	Jan. 2011	0.8*	0.62*	0.56
Annual areal rainfall (mm), n=7		0.81*	0.96*	0.92*

* Correlations significant at 95% level of confidence

** Annual runoff depth is the annual runoff per unit of a catchment area.

In addition to the spatial variability, there is also high temporal variability of runoff in the basin. We examined more than five peak flood events for each monitoring stations. Typical flood hydrographs are shown on Fig. 3.8. The flood hydrographs for the catchments in the basin showed that the largest part of the runoff in the majority of the monitored catchments took place in the form of flash floods (average flood duration lasting not more than 3-5 hours). Exception to this are flood events for the Gilgel Abay River (Fig. 3.8 (c)) and for the other major rivers in the floodplain (Fig. 3.8 (d)) where most of the flood discharges lasted more than 15 hours.

On average, 88% of the total runoff observed from the monitoring stations in 2012 occurred in the period of June-September (the rainy season in Ethiopia). The runoff response is smaller at the beginning of the rainy season (June) than towards the end, reaching its climax in August. The temporal variability of runoff is dealt in detail on the flowing sections in relation to the floodplains.

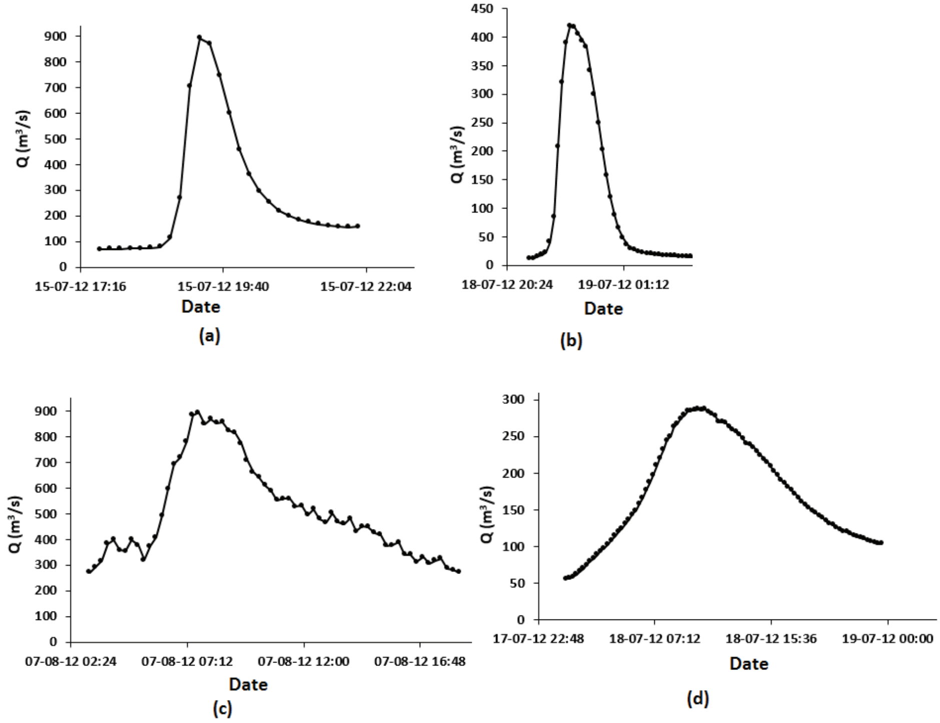


Figure 3.8: Typical flood hydrographs for (a) Gumara catchment at Wanzaye station, (b) Gelda catchment, (c) Gilgel Abay catchment at Picolo Station and (d) Gumara catchment at the lower station (in the floodplain)

3.3.3 Floodplain and river interactions

i) Temporal runoff variability in the river segments within the floodplain

The upstream and downstream measurement stations for Gumara, Rib and Megech Rivers are used to study the floodplain and river interactions (Fig. 3.1). The upstream stations are located at the transition from foot hills to the floodplain, whereas the downstream stations are located within the floodplain. It is important to remark that the difference in catchment area between the upstream and downstream stations (hereafter referred as incremental area) includes both the floodplain and a hilly area (Fig. 3.1, Table 3.6).

The measured monthly runoff for the upper and lower stations and for the incremental area (difference of the two) (Fig. 3.9) indicates that the incremental area (comprising large tracts of floodplain) abstracts nearly all river discharge in the dry season. At the beginning of the rainy season (early June), the incremental areas of Gumara and Megech (containing large floodplain areas) do not contribute runoff in June and July, rather abstraction of runoff from the upland flow is observed.

Table 3.6: Part of the floodplain in the incremental area

Catchment	Catchment area (km^2)			Incremental area in the floodplain	
	Upstream station	Downstream station	Incremental area	(km^2)	(%)
Gumara	1235.6	1357	121.4	51	42
Rib	1173.7	1308.3	134.6	23	17
Megech	513.7	624	110.3	21	19

With cumulative rainfall and lake level, flooding becomes a frequent phenomenon in the downstream reach of these rivers (SMEC, 2007; Assefa et al., 2008). In this study, frequent flood events have been particularly noticed in July and August. In August and September, large volumes of water (230 million m^3) are contributed by the incremental areas (Fig. 3.9).

The variation of the flows between upstream and downstream stations during the other months (dry period of the year), when the downstream stations have very low or no flows as compared to the upstream stations, is due to high abstraction of water for smallholder irrigation in the floodplain, which is common in Ethiopia during the dry season (Kay, 2001). Field observations also confirmed this widespread activity of the farmers along the river courses in the floodplain, tapping river water using motor pumps and irrigating the adjacent plots of land.

To further understand the hydrological conditions in the floodplain and possible effects on the downstream river discharges, water balance calculations have been made separately for the floodplain area, through subtracting runoff contributions from that part of the incremental area that lies in the hills (outside the floodplain) using the monthly runoff coefficients of the respective upstream catchments (Fig. 3.10).

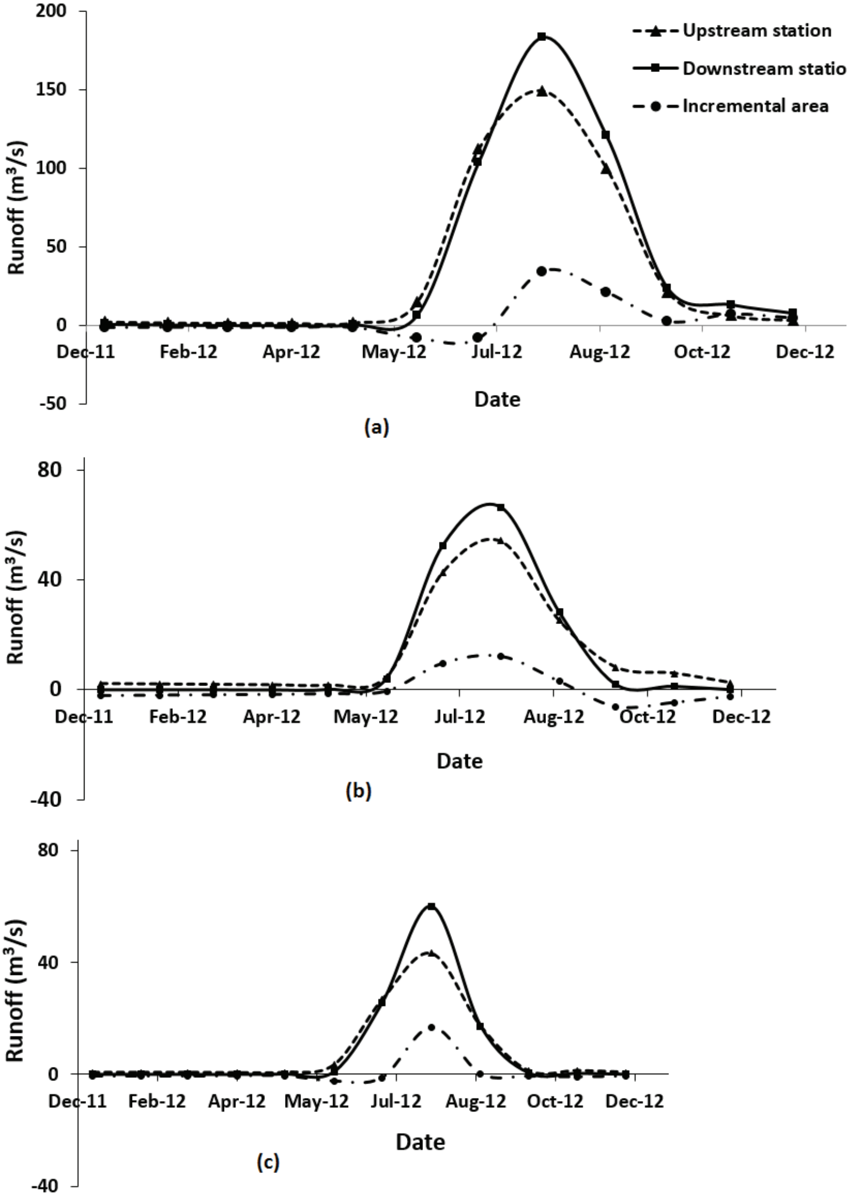


Figure 3.9: Temporal variability of runoff volumes at the upstream and downstream stations of Gumara (a), Rib (b) and Megech (c) rivers.

Fig. 3.10 indicates that the runoff response is smaller at the beginning of the rainy season (June) than towards the end, in line with findings of recent studies in Ethiopia (e.g. Tewodros et al., 2009; Zenebe et al., 2013). The temporal variability of runoff is likely to be influenced by temporal variation of catchment characteristics (particularly soil moisture and vegetation cover). Other factors like rainfall intensity and surface properties of soils can also affect the runoff in the different catchments, and it is difficult to clearly show the impacts here due to data constraints.

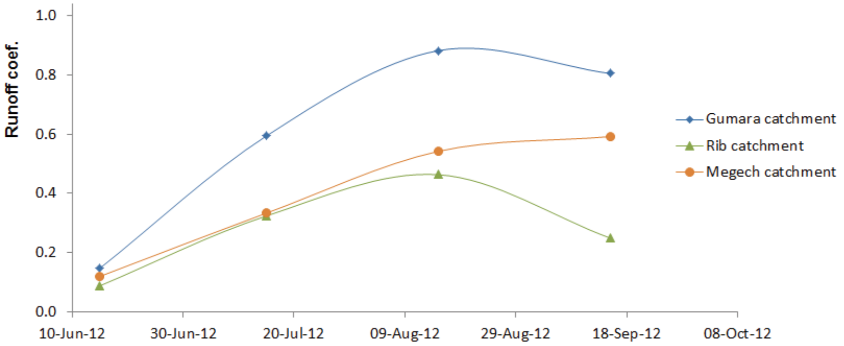


Figure 3.10: Monthly runoff coefficients for the upstream stations.

Runoff conditions in the floodplain are assessed by considering the difference in measured runoff between the upper and lower stations and the runoff for the catchment area between the two stations, but outside the floodplain:

$$Q_d = Q_u + Q_i \quad (3.6)$$

where Q_d (m^3/month) is runoff for the station in the floodplain (downstream station), Q_u (m^3/month) is runoff for upstream station and Q_i (m^3/month) is runoff contributed from the catchment in between (incremental area).

Q_i is portioned as:

$$Qi = Q_h + Q_f \quad (3.7)$$

where Q_i is as defined above (runoff from the incremental area), Q_h (m^3/month) is runoff from incremental area that lies in the hills and Q_f (m^3/month) is runoff from the floodplain area.

A simplified monthly water balance equation for the incremental area can be written as:

$$\Delta S = P_m A_i - (Q_d - Q_u) - ET_m A_i \quad (3.8)$$

where, P_m = monthly precipitation on the incremental area (m/month)

Q_u = monthly runoff from upstream station (m^3/month), as defined in Equation (3.6)

Q_d = monthly runoff from downstream station (m^3/month)

ET_m = monthly evapotranspiration on the incremental area (m/month)

ΔS = monthly storage changes of the incremental area (m^3/month)

Ai = the incremental area (m^2)

The monthly evolution of storage changes on the incremental area was calculated from Equation (3.8) using discharge measured at the upstream and downstream stations, precipitation data and evapotranspiration (Table 3.4).

From Equations (3.6), (3.7) and (3.8), the runoff from the floodplain area is:

$$Q_f = P_m A_i - Q_h - ET_m A_i - \Delta S \qquad (3.9)$$

The floodplain in all of the downstream river reaches (Gumara, Rib and Megech) has no runoff response in June, the condition still continues until end of July for Gumara and Rib (Table 3.7).

Table 3.7: Runoff response of the floodplains on monthly basis

Floodplain location	Runoff from floodplain [1] (mm) for river discharge at downstream station				Monthly rainfall(mm)				Change in storage in the floodplain (mm)			
	June	July	Aug.	Sept.	June	July	Aug.	Sept.	June	July	Aug	Sept.
Gumara	-451	-825	1339	746	155.7	455.2	381.6	267	465	1176	-1062	-596
Rib	-105	547	605	110	142	430.2	394.5	214.8	-65	-346	-441	-154
Megech	-372	-679	1344	-338	145.5	375	334.5	146.4	172	792	-1273	199

[1] Negative sign indicates flow abstraction, positive sign indicates contribution

The discharge measurements at the upstream and downstream stations and the water balance studies show a deficit in runoff of 809 mm in June and July for all the stations with a corresponding increase in floodplain storage of 992 mm (Table 3.7). This is likely because of overtopping of river banks during frequent flooding on the upstream reaches, which is then stored as surface or groundwater in the floodplain. Hence, the floodplain behaves as an abstractor (flood retention) in June and July. Excessive runoff contribution in August to the downstream stations is observed from Table 3.7, and the change in storage has decreased in all the stations for the floodplain. This is an additional indication that the floodplain is acting as a reservoir, retaining flood water (in the form of surface and soil storage) until it is full and later releasing the stored water back to the rivers. This shows that the likely hydrological processes in the floodplain are that at the beginning of the rainy season, the floodplain is recharged with groundwater, supplied by the higher elevated areas. The floodplain is also recharged by infiltration of rainfall and by the rivers that release water to the floodplains as overbank flows. Proceeding to the main rainfall of July and August, these recharging components are still active and contribute to the floodplain aquifer's saturation. At this point, part of groundwater is still flowing into the lake and part of it is released into the rivers that are the main draining systems of the floodplain. During the saturation periods (end of July and August), floods do not supply the floodplain aquifers as they are saturated, nor are they fed by them given the hydrostatic difference (the rivers are higher than the water table in the floodplain). Therefore, during floods accumulation of excess water on the surface of the floodplain that spills over the river banks takes place, which will later partly flow back to the rivers once the flood recedes, and partly will be lost as evapotranspiration. It seems that until the middle to end of July, the dominant hydrological process in the floodplain is recharge of the floodplain, and runoff response from the floodplain starts after that moment.

As compared to the Gumara floodplain, the Rib floodplain responded quickly to the runoff contribution (probably because of the smaller floodplain area, Table 3.6), while the Megech floodplain contributes to runoff only in August.

ii) Floodplain water balance on seasonal and annual basis

Assuming that the groundwater catchment is the same as the river catchment, the rainy season (June to September) runoff response of the floodplain in Lower Gumara (Table 3.8) is similar to its upstream catchment with respect to its runoff coefficient (Fig. 3.6), but its annual water balance shows an increment in the runoff response. This is because of the effect of the springs located at the foothills of the catchment, downstream of the upstream station. These springs are the Wanzaye and Gurambaye springs from the Guna shield in the Lake Tana basin (Kebede, 2013).

Rib floodplain runoff response is very high in the rainy season, whereas it is totally absent for the floodplain in the Megech catchments. The reasons are not clear; probably there is inflow to the Rib floodplain from the adjacent catchment. The adjacent hills have no definite water ways and simply drain to the floodplain (SMEC, 2007) which then might have effect on the downstream station.

Table 3.8: Summary of floodplain water balance

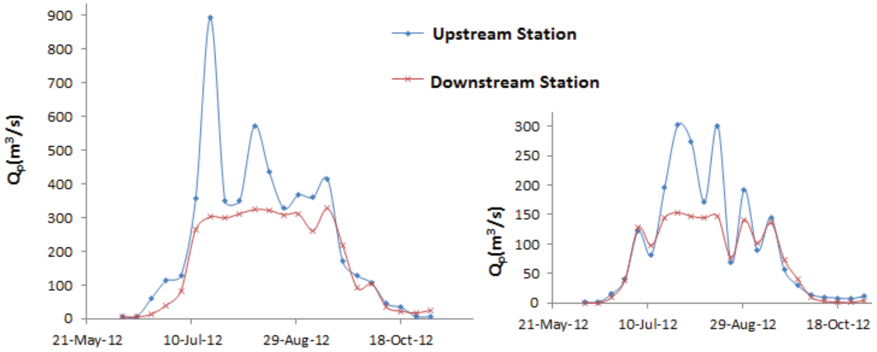
Floodplain	Catchment area (km^2)	Seasonal water balance [1] (mm) for river discharge at downstream station	Seasonal[1] rainfall (mm)	Seasonal[1] runoff coefficient	2012 water balance (mm) for river discharge at downstream station	2012 rainfall (mm)	2012 total annual runoff coefficient
Gumara	51	808	1260	0.64	1144	1348	0.85
Rib	23	1166	1181	0.98	-1908	1264	0
Megech	21	-45	1001	0	-982	1154	0

[1] June to September 2012

Another striking observation is that, in total, there is no runoff contribution from the floodplains of these catchments (see Table 3.8). This can mainly be attributed to the partial or complete abstraction of flows at the upstream end during the dry seasons for irrigation. This has its implications on the water balance of Lake Tana. Some previous works on the water balance studies of Lake Tana (Kebede et al., 2006; SMEC, 2007) considered the floodplain as a source of high water loss by evapotranspiration. This is also observed in this study from the annual water balance of the floodplains in the Rib and Megech catchments. However, the conclusion of no runoff contribution to the lake cannot be extrapolated to the complete floodplain in the basin, as this is not the case for the Gumara floodplain, where river flow is sustained by important springs that receive their water from upstream areas.

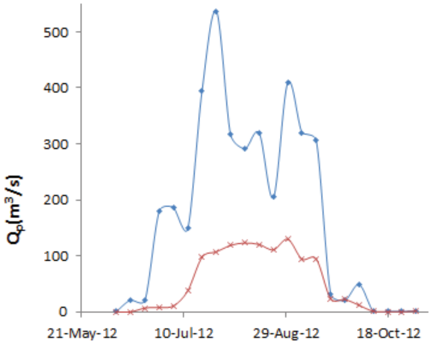
iii) The floodplain as regulator of floods

The analysis of weekly peak floods (Q_P) for the months of June to October (Fig.3.11) indicates that magnitude and variability of peak flow discharges in the floodplains (downstream stations) are on average 71 m^3/s (or 30%) smaller than the corresponding peak flow discharges at the upstream stations. Obviously, the peak discharges and the shapes of the flood hydrographs change as flood waves move downstream in the stream channels due to the routing process. However, it is less likely that the channel routing effect, for a reach distance of less than 15 km, can result in such a very pronounced reduction in flood magnitudes at the downstream station. The more likely explanation is that the actual peak discharges experienced in the rivers are very much affected by the flood storage within the floodplain. Therefore, the peak discharges of rivers in the floodplain of Lake Tana basin are buffered by the floodplain.



(a) Gumara River

(b) Rib River



(c) Megech River

Figure 3.11: Weekly peak flow discharges (Q_p) at upstream and downstream stations for Gumara (a), Rib (b) and Megech (c) rivers.

3.4 Conclusions

The river discharge observations at 12 stations in the Lake Tana basin have shown the spatial and temporal variability of runoff in the basin, owing to variations in climatic factors (mainly rainfall). The total annual runoff coefficients ranged between 0.23 and

0.81 for the year 2012. Some catchments in the basin were observed to behave differently for runoff response compared to other catchments having comparable rainfall depths, indicating that catchment properties are also important factors affecting runoff discharge. We found that runoff varied with drainage density, lithology and land use/land cover conditions. Drainage density and percentage of open field (dominant cultivated land without other important land use) increased runoff, whereas hilly topography, moderate cultivation and grassland cover lead to a decrease in runoff. The runoff coefficients increased from June to August and decreased afterwards.

The three studied floodplains (Gumara, Rib and Megech Rivers) abstracted 809 mm water with a corresponding increase in floodplain storage of 992 mm during the beginning of the rainy season (June to July) and released important discharge starting from August till mid-September. However, the analysis of the annual water balance pointed out that runoff contribution from the Rib and Megech floodplains is negligible, because of water abstraction for irrigation by adjacent smallholder farmers and high evapotranspiration loss in the floodplain. Due to considerable input from the springs downstream of the upper Gumara station, the floodplain of Gumara River has contributed about 1140 mm of runoff in 2012 to Gumara River at the floodplain station. The study demonstrated that the floodplain acts as storage of flood water, and consequently magnitude of peak floods were on average 71 m^3/s (or 30%) smaller in the lower than in the upper stations.

The findings in this study provide a better understanding of runoff conditions in the floodplain, enhance the determination of the water balance of Lake Tana and contribute to the integrated management of the diverse agricultural, fauna and flora resources of the floodplain.

No similar studies have been made earlier for the floodplains around Lake Tana, and the detailed processes and interactions downstream close to the lake remain to be further investigated.

CHAPTER 4

4. Analyzing runoff processes through conceptual hydrological modelling[2]

Abstract

Understanding runoff processes in a basin is of paramount importance for the effective planning and management of water resources, in particular in data scarce regions, such as the Upper Blue Nile. Hydrological models representing the underlying hydrological processes can predict river discharges from ungauged catchments and allow for an understanding of the rainfall-runoff processes in those catchments. In this chapter, such a conceptual process-based hydrological model is developed and applied to the upper Gumara and Gilgel Abay catchments (both located within the Lake Tana basin) to study the runoff mechanisms and rainfall-runoff processes in the basin. Topography is considered as a proxy for the variability of most of the catchment characteristics. We divided the catchments into different runoff production areas using topographic criteria. Impermeable surfaces (rock outcrops and hard soil pans, common in the Upper Blue Nile basin) were considered separately in the conceptual model. Based on model results, it can be inferred that about 65% of the runoff appears in the form of interflow in the Gumara study catchment, and baseflow constitutes the larger proportion of runoff (44-48%) in the Gilgel Abay catchment. Direct runoff represents a smaller fraction of the runoff in both catchments (18-19% for the Gumara, and 20% for the Gilgel Abay) and most of this direct runoff is generated through infiltration excess runoff mechanism from the impermeable rocks or hard soil pans. The study reveals that the hillslopes are recharge areas (sources of interflow and deep percolation) and direct runoff as saturated excess flow prevails from the flat slope areas. Overall, the model study suggests that identifying the catchments into different runoff production areas based on topography and including

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[2] Adapted from Hydrology and Earth System Sciences (HESS)
Dessie, M., Verhoest, N.E.C., Pauwels, V.R.N., Admasu, T., Poesen, J., Adgo, E., Deckers, J., Nyssen, J., 2014. Analyzing runoff processes through conceptual hydrological modelling in the Upper Blue Nile basin, Ethiopia. Hydrol. Earth Syst. Sci., 18, 5149-5167, doi: 10.5194/hess-18-5149-2014, 2014.

the impermeable rocky areas separately in the modeling process mimics well the rainfall-runoff process in the Upper Blue Nile basin and brings a useful result for operational management of water resources in this data scarce region.

4.1 Introduction

The Upper Blue Nile basin, the largest tributary of the Nile River, covers a drainage area of 176 000 km^2 and contributes more than 50 percent of the long term river flow of the Main Nile (Conway, 2000). The basin (Fig. 4.1a) drains the central and south-western highlands of Ethiopia. The Ethiopian government is pursuing plans and programs to use the water resource potential of the basin for hydropower and irrigation in an effort to substantially reduce poverty and increase agricultural production. The Grand Ethiopian Renaissance Dam near the Ethiopian–Sudan border is currently under construction and several other water resource development projects are underway in its sub-basins.

Owing to such rapidly developing water resource projects in the basin, there is an increasing need for the management of the available water resources in order to boost agricultural production and to meet the demand for electrical power. Sustainable planning and development of the resources depend largely on the understanding of the interplay between the hydrological processes and the availability of adequate data on river discharges in the basin. However, the available hydrological data are limited (for example, presently about 42% of the Lake Tana sub-basin, source of the Blue Nile, is gauged by the Ministry of Water Resources of Ethiopia). Furthermore, research efforts performed so far in the Upper Blue Nile basin with respect to the basin characteristics, hydrology and climatic conditions are scanty and fragmented (Johnson and Curtis, 1994; Conway, 1997; Mishra and Hata, 2006; Antar et al., 2006). Hydrological models that allow for a description of the hydrology of the region play an important role in predicting river discharges from ungauged catchments, and understanding the rainfall-runoff processes in the catchments to enhance hydrological and water resources analysis. As such, a number of models have been developed and applied to study the water balance, soil erosion, climate and environmental changes in the Blue Nile basin (e.g. Johnson and Curtis, 1994; Kebede et al., 2006; Mishra and Hata, 2006; Conway, 1997; Kim and Kaluarachchi, 2008; Collick et al., 2009; Steenhuis et al., 2009; Tekleab et al., 2011 Tilahun et al., 2013).

The Soil and Water Assessment Tool (SWAT) and the Hydrologiska Byråns Vattenbalansavdelning Integrated Hydrological Modelling System (HBV-IHMS) models have been applied in the basin (Setegn et al., 2008; Wale et al., 2009; Uhlenbrook et al., 2010). The SWAT model is based on the Soil Conservation Service (SCS) runoff curve number approach, where the parameter values are obtained empirically from plot data in the United States with a temperate climate. Liu et al. (2008) studied the rainfall-runoff relationships for the three Soil Conservation Research Project (SCRP) watersheds (Hurni, 1984) in the Ethiopian highlands and showed the limitations of using such models, developed in temperate climates, in monsoonal Ethiopia. Adjusted runoff curve numbers for steep slopes with natural vegetation in north Ethiopia were reported by Descheemaeker et al. (2008).

Using a simple runoff-rainfall relation to estimate inflows to the Lake Tana from ungauged catchments, Kebede et al. (2006) computed the water balance of Lake Tana. However, hills and floodplains were not differentiated in their simplified runoff-rainfall relations. Mishra et al. (2004) and Conway (1997) developed grid-based water balance models for the Blue Nile basin, using a monthly time step, to study the spatial variability of flow parameters and the sensitivity of runoff to climate changes. In both models, the role of topography was not incorporated, and in the model of Conway (1997) soil characteristics are assumed spatially invariant. Very few of the models discussed above attempted to identify the catchments into different hydrological regimes based on the relevant landscape characteristics to study the runoff mechanisms and the hydrological processes in the basin. Landscape characteristics can lead into conceptual structures and relationships or the conceptual hydrological models can benefit from them (Beven, 2001). Istanbulluoglu and Bras (2005) considered topography as a template for various landscape processes that include hydrologic, ecologic, and biologic phenomena. This is more appealing to the Ethiopian highlands, in particular to the Upper Blue Nile basin, as farming and farm drainage methodologies, soil and water conservation works, soil properties, vegetation, and drainage patterns and density are much linked to topography in the Ethiopian highlands. Therefore, it remains necessary to investigate the hydrological processes in the Blue Nile basin taking topography as a proxy for the variability of most of the catchment characteristics. The objective of this chapter is to study runoff mechanisms in the Upper Blue Nile basin (Lake Tana sub-basin) using topography as the dominant landscape component and classify a catchment (as steep, medium and flat slope areas) into different runoff production areas. The study tries to identify the dominant rainfall-runoff mechanism on the hillslopes (steep and medium slope areas) and the valley bottoms (flat areas). A considerable portion of the mountainous areas in the Upper Blue Nile basin consists of impermeable rocks and hard soil pans leading to a different runoff process. This chapter further investigates the contribution of such landscapes in the rainfall-runoff process by including a class for these impermeable rock and hard soil surfaces in the conceptual hydrological model. This approach has not so far been tested in the Upper Blue Nile basin. However, similar methodologies to the conceptual hydrological model development are discussed by Savenije (2010). Furthermore, it is necessary to obtain better quality river discharge data in the basin. In this chapter, we will face all these challenges. The conceptual hydrological model for the rainfall-runoff studies of the basin is calibrated using good quality discharge data obtained from recently established measurement stations. These outcomes positively add to the existing knowledge and contribute to the development of water resources plans and decision making in the basin.

4.2 Description of study catchments

The study catchments (Fig. 4.1b), where the model developed is applied, are located in the Lake Tana basin, the source of the Blue Nile River. The Lake Tana basin consists predominantly of the Gilgel Abay, Gumara, Rib and Megech Rivers. About 93% of the annual inflow to Lake Tana is believed to come from these rivers (Kebede et al., 2006), and better understanding of the hydrology of these rivers plays a crucial role for an efficient management of the lake and its basin. Two of the sub-catchments (Gumara and Gilgel Abay) were selected for this study, in order to represent the hilly and mountainous lands of the southern and eastern parts of the sub-basin as the bulk of it is located here (Fig.4.1b), and to optimally use the available data. For both sub-catchments, large parts of their territory are intensively cultivated. The lower floodplains in these catchments with their buffering capacity are not considered by this study, but were discussed in Chapter 3 and Dessie et al. (2014a).

The Gilgel Abay catchment (Fig. 4.1b) covers an area of 1659 km^2 at the gauging station near Picolo, with elevations ranging between 1800 and 3524 m a.s.l. Soils are characterized by clay, clay loam and silt loam textures, each texture sharing similar proportions of the catchment area (Bitew and Gebremichael, 2011). The majority of the catchment is a basalt plateau with gentle slopes, while the southern part has a rugged topography.

The Gumara catchment covers part of the eastern side of the Lake Tana basin. At its upper and middle portion, it has mountainous, highly rugged and dissected topography with steep slopes. The lower part is a valley floor with flat to gentle slopes. Elevation in the catchment varies from 1780 to 3700 m a.s.l. At the upper gauging station (Fig. 4.1b), the catchment area is 1236 km^2. Two independent studies found very homogeneous textures of the soils in this catchment. BCEOM (1998a) described it as dominantly clay with sandy clay soil at some places in the catchment, while soil data collected by Miserez (2013) show that texture is clay and clay loam. In the hilly catchments, clay soils are essentially Nitisols which do not present cracking properties as opposed to lowland Vertisols (Miserez, 2013).

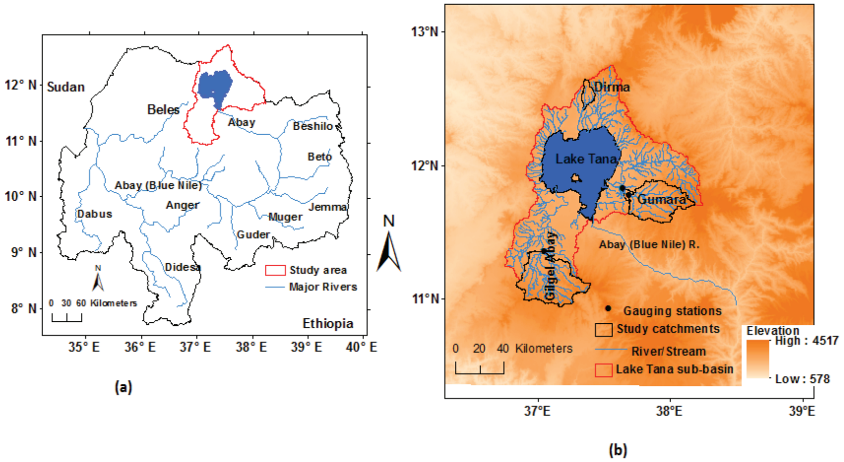

Figure 4.1: The Upper Blue Nile basin and the Lake Tana sub-basin (a) and the study catchments and the gauging stations in the Lake Tana sub-basin georeferenced on the SRTM DEM (b)

Based on rainfall data from the Dangila and Bahir Dar stations (Fig. 2.11), observed in the period 2000 to 2011, mean annual rainfall is ca. 1500 mm, with more than 80% of the annual rainfall concentrated from June to September. Geologically, the catchments consist of Tertiary and Quaternary igneous rocks, as well as Quaternary sediments. The rivers in the hilly areas are generally bedrock rivers, whereas in the floodplain the rivers meander and sometimes braid (Poppe et al., 2013).

4.3 Model development

The model developed is based on a simple water balance approach and the studies by Jothityangkoon et al. (2001), Krasnostein and Oldham (2004) and Fenicia et al. (2008). The setup of this model is shown in Fig. 4.2. In this modeling approach, the catchment is first split into soil surface and impermeable surface (these are areas with little or no soil cover and bedrock outcropping in the catchment as well as soils with well-developed tillage pans). The runoff from the presumed impermeable areas is modeled as infiltration excess (Hortonian flow) runoff and is represented as *QSe2*. The other component of the catchment, recognized as the soil surface, is further divided into three using topographic criteria (slope), considering topography as a proxy for the variability of most of the catchment characteristics. Here, two reservoirs are introduced (the soil reservoir and the groundwater reservoir). The slow reacting reservoir (or the groundwater reservoir) is set to be common to all of the three slope based divisions of the catchment as it is quite inconsistent to separate the groundwater system in the catchment. The catchment buckets (reservoirs) and the conceptual runoff processes are depicted in Fig. 4.2 (b) and (c).

Jothityangkoon et al. (2001) conceptualized the upper soil layer (further referred to as the soil reservoir) as a ‘leaky bucket’. By adding a groundwater reservoir (Krasnostein and Oldham, 2004), the conceptual model for modelling the runoff at the catchment outlet was developed.

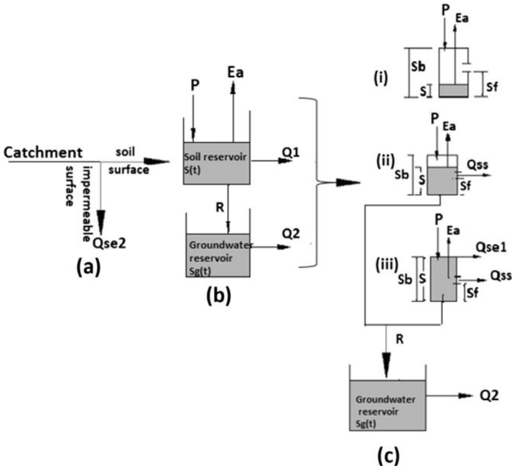

Figure 4.2: The modeling approach showing (a) partitioning of a catchment into different runoff production areas, (b) conceptual model configuration of the soil surface at an outlet of a catchment and (c) inflows and outflows for the soil reservoir when the soil water storage capacity is (i) below field storage capacity, (ii) greater than field storage capacity and (iii) greater than the maximum soil water storage (after Krasnostein and Oldham, 2004).

In Fig. 4.2, Q_1 [mm/day] is the sum of direct runoff and interflow in the soil reservoir, Q_2 [mm/day] is the baseflow from the groundwater reservoir, *QSe2* is the direct runoff from impermeable surface of the catchment and the sum of Q_1 , Q_2 and *QSe2* forms the total river discharge, *Q* [mm/day], at the outlet of a catchment.

The water storage at any time *t* within the soil reservoir, *S(t)* in mm, is determined by the precipitation (P , in mm/day), evapotranspiration (E_a, in mm/day), and other catchment controlled outputs (Fig. 4.2c (i-iii)). When the storage depth exceeds the field storage capacity (S_f, in mm), precipitation is assumed to be partly transformed into subsurface runoff, to represent inter- or subsurface flow (Q_{ss}, in mm/day), and partly into deep percolation or recharge (*R,* in mm/day) to the groundwater (Fig. 4.2cii). When the soil reservoir fills completely, and the inflows exceed the outflows, surface runoff (Q_{se1}, in mm/day) is generated.

Quantitatively, the depth of water stored in the soil, *S (t)*, evolves over time using the water balance:

$$S(t) = S(t - \Delta t) + (\mathrm{P} - E_a - Q_{\mathrm{ss}} - Q_{\mathrm{se1}} - R)\Delta t \qquad (4.1)$$

where P is the precipitation [mm/day], E_a is the actual evapotranspiration [mm/day], $S(t-\Delta t)$ is the previous time step storage [mm], Q_{ss} is the interflow or subsurface runoff [mm/day], Q_{se1} is the direct or overland flow from the soil reservoir [mm/day], R is deep percolation or recharge to the substrata and groundwater [mm/day], and Δt is the time step equal to one day.

Different studies show that some part of the interflow water from the steep hills appears at the hill bottoms during wet periods in the form of increased moisture content or overland flow (Mehta et al., 2004; Frankenberger et al., 1999; Bayabil et al., 2010; Tilahun et al., 2013). These findings reveal that the hill bottoms receive additional inputs to the soil reservoir from the steep upper parts of the hills besides the rainfall. In this modelling approach, it is assumed that steep hills first recharge the medium slope sections, and consequently the medium slope surfaces recharge the flat regions (valley bottoms). The magnitude of the recharge (Q_r, in mm/d) is modelled as:

$$Q_r = \alpha Q_{ss} \tag{4.2}$$

where α (-) is interflow partitioning parameter and Q_{ss} is as defined above. Equation (4.1) is, therefore, modified for the medium slope and flat surfaces as

$$S(t) = S(t-\Delta t) + (\text{P} + Q_{\text{r}} - E_a - Q_{\text{ss}} - Q_{\text{se1}} - R)\Delta t \tag{4.3}$$

4.3.1 Actual evapotranspiration

During wet periods, when the depth of available water exceeds the maximum available soil storage capacity (S_b, in mm), the actual evapotranspiration is equal to the potential evapotranspiration (E_p, in mm/day). When $S(t)$ is lower than S_b, E_a is assumed to decrease linearly with moisture content as follows (Steenhuis and van der Molen, 1986):

$$E_a = E_p\left(\frac{S(t)}{S_b}\right) \tag{4.4}$$

$$S_b = D\phi \tag{4.5}$$

where D is the soil depth [mm] and ϕ is the soil porosity (-).

4.3.2 Subsurface runoff

Subsurface runoff, Q_{ss} [mm/day], occurs only when the storage depth exceeds the field storage capacity (S_f, in mm). It is calculated as the difference between the storage and the field storage capacity, divided by the response time (T_r) of the catchment with respect to subsurface flow (Jothityangkoon et al., 2001):

$$
\begin{aligned}
&Q_{ss} = \frac{S(t) - S_f}{T_r}, \text{ when } \mathrm{S(t)} > \mathrm{S}_f \\
&Q_{ss} = 0, \quad \text{when } \mathrm{S(t)} \le \mathrm{S_f}
\end{aligned}
\tag{4.6}
$$

The field storage capacity of the soil reservoir, S_f [mm], is calculated by

$$S_{\mathrm{f}} = F_c D \tag{4.7}$$

where F_c (-) is the field capacity of the soil (dimensionless).

The catchment response time is the time taken by the excess water in the soil to be released from the soil and drained out from the catchment. This response time depends on the properties of the soil and the topography of the system, and the subsurface flow velocity (V_b, in mm/day) can be expressed as

$$V_b = \frac{L}{T_r} \tag{4.8}$$

where L is the average slope length of the catchment [mm]. From Darcy's law in saturated soils, V_b is also given as

$$V_b = K_s i \tag{4.9}$$

where K_s is the saturated hydraulic conductivity of the soil [mm/day] and i is the hydraulic gradient, which is approximated by the average slope gradient (G) of the catchment.

Brookes et al. (2004) analyzed the variability of saturated hydraulic conductivity with depth, and they found large K_s values near the surface or root zone layer and the transmissivity that decreases exponentially with depth. Accordingly, a variation is made between the upper soil layer (that affects interflow) and deep soil layer (percolation to groundwater) hydraulic conductivities. The permeability (K, in mm/day) of the upper soil layer for the interflow under different soil water conditions is modelled as:

$$K = K_{s,u}\left(1 - e^{-\beta \frac{S(\mathrm{t})}{S_b}}\right) \tag{4.10}$$

where β is a dimensionless parameter, and $K_{s,u}$ [mm/day] is the saturated hydraulic conductivity of the upper soil layer, both of which are to be calibrated.

The response time (T_r) in Equation (4.6) is, hence, approximated from Equations (4.8), (4.9) and (4.10) as

$$T_r = \frac{L}{GK} \tag{4.11}$$

where L and K are as defined in Equations (4.8) and (4.10) and G is average slope gradient of the catchment.

The deep percolation or recharge to groundwater (R, in mm/day) under varying soil water content conditions is modelled as:

$$R = K_{s,e}\left(1 - e^{-\gamma \frac{S(t)}{S_b}}\right) \tag{4.12}$$

where γ a dimensionless parameter, and $K_{s,e}$ [mm/day] is the saturated hydraulic conductivity of the deep soil layer, which is to be estimated from the aquifer properties of the catchments. This equation is identical to Equation (4.10) such that in both cases it is assumed that conductivities vary exponentially under varying soil water content conditions but with different magnitudes.

4.3.3 Saturated excess runoff

Saturated excess runoff or surface runoff **(**Q_{se1}**,** in mm/day) is calculated as the depth of water that exceeds the total water storage in the soil reservoir at each time step (Jothityangkoon et al., 2001; Krasnostein and Oldham, 2004).

$$\begin{aligned} Q_{se1} &= \frac{S(t) - S_{\mathrm{b}}}{\Delta t} \text{ , when } S(\mathrm{t}) > S_{\mathrm{b}} \\ Q_{se1} &= 0 \text{ , when } S(\mathrm{t}) \le S_{\mathrm{b}} \end{aligned} \tag{4.13}$$

4.3.4 Surface runoff from the impermeable areas

Field visits on the Upper Blue Nile basin (including the study catchments) revealed the existence of exposed surfaces that cause strong runoff response. These are areas with little or no soil cover and bedrock outcropping in some parts of the catchment as well as soils with well-developed tillage pans (Temesgen et al., 2012a, 2012b) (Fig. 4.3). Hence, runoff from these almost impermeable areas is modeled as infiltration excess (Hortonian flow) runoff with a very small amount of retention before runoff occurs (Steenhuis et al., 2009). The surface runoff from these areas ($QSe2$, in mm/day) is calculated as

$$\begin{aligned} QSe2 &= P - E_{\mathrm{p}} \text{ , when } P > E_{\mathrm{p}} \\ QSe2 &= 0 \text{ , when } P \leq E_{\mathrm{p}} \end{aligned} \tag{4.14}$$

where P and E_p [mm/day] are as defined above. The impermeable portion of the catchment area (A_r, in km^2) is modelled from the total catchment area (A_t, in km^2) as

$$A_r = \lambda A_t \tag{4.15}$$

where λ is the fraction of impermeable surface within the catchment.

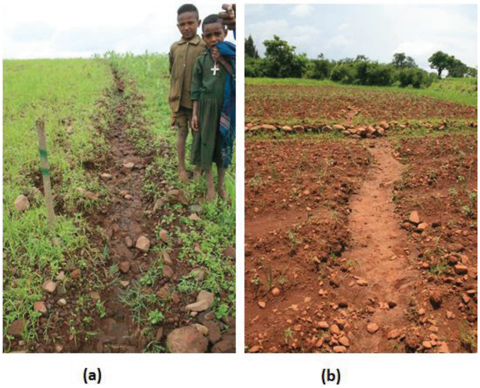

Figure 4. 3: Typical surfaces with poor infiltration on hillslopes in the Gumara catchment: (a) shallow soil overlying bedrock, and (b) plough pan with typical plough marks. The occurrence of high runoff response on these surfaces is evidenced by the presence of rill erosion (Photos: Elise Monsieurs)

4.3.5 Groundwater reservoir and baseflow

The introduction of a deep groundwater storage (Fig. 4.2b) helps to improve low flow predictions. This baseflow reservoir is assumed to act as a non-linear reservoir (Wittenberg, 1999) and its outflow, Q_2 [mm/day], and storage, S_g [mm], are related as

$$Q_2 = \frac{S_{g(t)}^{k1}}{\Delta t} \tag{4.16}$$

where k_1 is a dimensionless model parameter. The water balance of the slow reacting reservoir (groundwater reservoir) is given by

$$S_{g(t)} = S_{g(t-\Delta t)} + (\mathrm{R} - Q_2)\Delta t \qquad (4.17)$$

where $S_{g(t)}$ [mm] is the groundwater storage at the given time step, $S_{g(t-\Delta t)}$ [mm] is the previous time step groundwater storage , R [mm/day] is the deep percolation, as given by Equation (4.12).

In total the model has seven parameters:

(i) Parameters for the recharge (α_1 and α_2): In the three slope classification, α_1 is to consider for the recharge from the steeply slope into the medium slope surface and α_2 is for the recharge from the medium slope surface into the flat surface. There is no parameter for the steeply slope surface since there is no surface that recharges it. So, there are two parameters for the three slope classifications.

(ii) Parameter for the impermeable surface of the catchment (λ)

The catchment is divided into two surfaces (impermeable surface with no or little soil cover and the soil surface). The parameter λ is introduced to represent the fraction of impermeable surface within the total catchment and this part of the catchment is not classified as steeply, medium slopes and flat surfaces since the classification of this part of the catchment into such classes is not important. So we have one parameter.

(iii) The parameters β, γ, k_1 and $K_{s,u}$

The parameters β and γ are introduced to account for variability of permeability and deep percolation of soil with soil water storage. k_1 relates discharge and storage for the ground water and $K_{s,u}$ is the saturated hydraulic conductivity in the upper soil layer. We assumed that these parameters are less influenced by topography and each model parameter is assumed to be same for each slope classification of the catchment. Moreover, it is quite inconsistent to separate the groundwater system in the catchment. Therefore, all the three slope-based classified sub-catchments share the same groundwater reservoir.

In this modeling approach, stream-groundwater interactions are assumed to be minimal and the groundwater is assumed to recharge the streams from deep percolation of rainfall on the catchments that produces baseflow of the rivers/streams. The storage effect of the streams when considered on the basis of average daily flows of the streams is assumed to be negligible and hence streamflow routing was not considered for such smaller streams.

4.3.6 Total river discharge

The total river discharge (Q_t, in mm/day) at the outlet of the catchments is given by:

$$Q_t = Q_{ss} + Q_{se1} + QSe2 + Q_2 \qquad (4.18)$$

4. 4 Data inputs

The data needed for the model are classified into three types: topographical, soil, and hydrological data.

4.4.1 Topographical data

Steenhuis et al. (2009) found that overland flow in the Blue Nile basin is generated from saturated areas in the relatively flatter areas and from bedrock areas, while in the rest of the catchment all the rainfall infiltrates and is lost subsequently as evaporation, interflow or baseflow. Topographical processes have been found to be the dominant factors in affecting runoff in the Blue Nile Basin (Bayabil et al., 2010). We used topography of catchments as the main criterion to divide the catchment into different runoff production surfaces. Based on slope criteria (FAO, 2006), each study catchment was divided into three sub-catchments as steep (slope gradient > 30%), hilly or medium (slope gradient between 8 and 30%) and flat (slope gradient < 8%) to consider spatial variability in catchment properties and runoff generation mechanisms (Fig. 4. 4).

The 30 m by 30 m resolution Global Digital Elevation Model (GDEM) was used to define the topography (downloaded from the ASTER website, http://earthexplorer.usgs.gov/). The GDEM (Fig. 1b) was used to delineate and calculate the average slope gradient and average slope length of the catchments (topography-related inputs to the model).

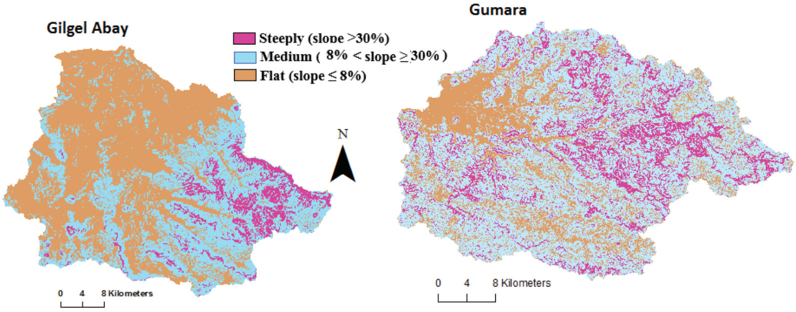

Figure 4.4: The three slope categories for the Gilgel Abay and Gumara catchments

4.4.2 Soil data

The model requires data on depth, porosity and field capacity of the soils. Soil depth and soil types data (Fig. 2.6 and Fig. 4.5) were obtained from the Abay River Basin integrated master plan study BCEOM (1998a).

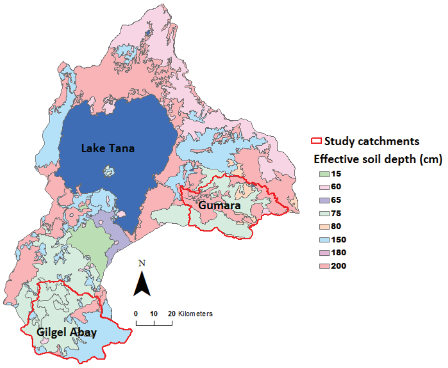

Figure 4.5: Soil depth in the Lake Tana basin and the study catchments (Source: BCEOM 1998a)

In this modeling philosophy, the soil depth is meant to represent the depth of water stored in the topmost layer (root zone) of the soil (Fig. 4.2). The porosity and field capacity of the soils were derived from soil texture based on the work of McWorter and Sunada (1997). For this, we determined the soil textures of the study catchments (Table 4.1) from the Abay River Basin integrated master plan study BCEOM (1998a). The soil depth data from BCEOM (1998a) for Gilgel Abay catchment show deeper soil depths for steeper slopes than other slope classes, which looks strange. However, the soil depth data collected from another source (woody biomass project in Ethiopia) also confirm similar pattern of soil depth with BCEOM (1998a) data.

The saturated hydraulic conductivity for the deep percolation (Equation 4.12) was estimated using ranges of conductivities given by Domenico and Schwartz (1990) for the saturated hydraulic conductivities of a deep soil layer (colluvial mantle on top of the igneous rock). A summary of the topographic, soil and saturated hydraulic conductivity data for the study catchments is provided in Table 4.1.

Table 4.1: Input data on topography, soil and saturated hydraulic conductivities for the study catchments as classified into different hydrological regimes using topography

Catchment	Slope class	Average slope (%)	Coverage from the total area (%)	Average Soil depth (m)	Dominant soil texture	Porosity	Field capacity	Saturated hydraulic conductivity $K_{s,e}$ (m/s)
Gilgel Abay	Level (slope$\leq$ 8%)	3.4	54	0.92	clay	0.46	0.36	$9.26\text{x}10^{-8}$
	Hilly ($8\% < \text{slope} \leq 30\%$)	15.9	38	1.29	clay to clay loam	0.42	0.32	
	Steeply (slope >30%)	41.4	8	1.49	clay loam to silt loam	0.4	0.26	
Gumara	Level (slope $\leq$ 8%)	4.0	24	1.5	clay	0.46	0.36	$1.16\text{x}10^{-8}$
	Hilly ($8\% < \text{slope} \leq 30\%$)	17.2	60	1.24	loam , silty clay	0.42	0.26	
	Steeply (slope >30%)	41.5	16	1.2	sandy loam	0.25	0.1	

4.4.3 Weather data

Daily precipitation is the key input meteorological data for the model. Other meteorological data like minimum and maximum air temperature, humidity, wind speed and duration of sunshine hours were also used to calculate the potential evapotranspiration, the other input variable to the model. All weather data were obtained from the Ethiopian National Meteorological Agency (NMA) for 13 stations located within and around the catchments. The location map of the rain gauge stations used for this study are depicted in Fig. 4.6. The data for most of the stations are consistent and continuous, particularly for the first class stations like Dangila, Adet and Debretabor. However, we encountered gaps in some stations like Sekela Station for some periods in the year. In such instances, only the rainfall data from the other stations were considered. Most of the rainfall stations in Gilgel Abay catchment are installed at the water divides and there is no station in the middle of the catchment. In this regard, the Gumara catchment has a higher density of rainfall stations. The areal rainfall distribution over the catchments was calculated using the Thiessen Polygon method (it is easy to use for daily time series data and to be consistent with SWAT model as bench mark for comparison as the model applies this method for areal rainfall estimation), and the potential evapotranspiration was calculated using the FAO Penman-Monteith method (Allen et al., 1998).

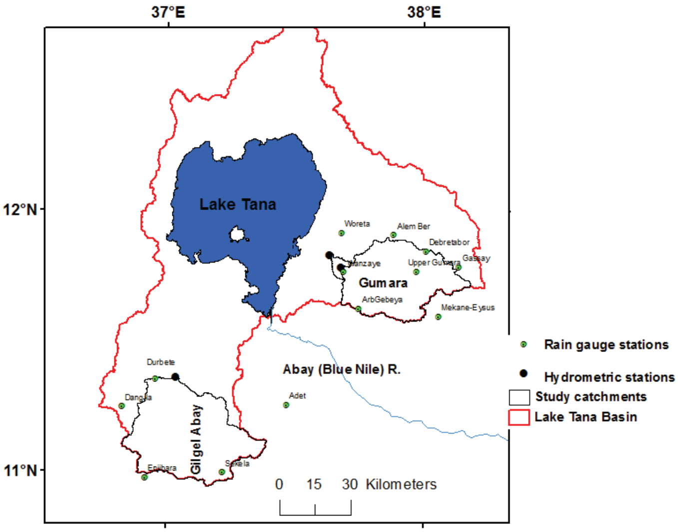

Figure 4.6: Location map of rainfall stations for the study catchments

4.4.4 River discharge

Starting from July 2011 water level was measured at the Wanzaye station (11.788073°N, 37.678266°E) on Gumara River and from December 2011 at the Picolo station (11.367088°N, 37.037497°E) on Gilgel Abay River. The water level measurements were made using Mini-Divers, automatic water level recorders, and manual readings from a staff gauge (three times a day, at 7 AM, 1 PM and 6 PM), following the procedures described by Zenebe et al. (2013).

Discharges were computed from the water levels using rating curves (Equations 4.20 and 4.21) for each station. The rating curves (Fig. 4.7) were calibrated based on detailed surveys of the cross-sections of the rivers and measurements of flow velocity at different flow stages, using the following commonly used expression:

$$Q = ah^{b} \qquad (4.19)$$

where a and b are fitting parameters and Q [m^3/s] and h [m] are discharge and water level respectively. The resulting rating curve equation for the Gumara catchment at the gauging station (Wanzaye Station) is:

$$Q = 44.1h^{1.965} \quad (R^2=0.997, n=12) \qquad (4.20)$$

and for Gilgel Abay catchment at Picolo Station:

$$Q = 70.39\, h^{2.105} \quad (R^2=0.985, n=14) \qquad (4.21)$$

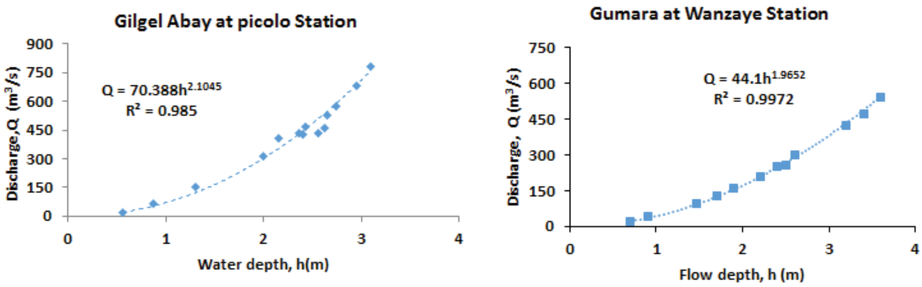

Figure 4.7: Stage-Discharge relationship (rating curves) for Gilgel Abay at Picolo and Gumara at Wanzaye Stations

Compared to the discharge data that have been gathered in the past, the discharge data that are acquired for this study are of superior quality, since a high time resolution during the measurement has been used. This minimizes the risk of missed peaks, particularly during the night. Furthermore, frequent supervision was also made during the data collection campaign. Hence, these data were used for the model calibration. Discharge data collected before December 2011 were obtained for nearby stations from the Hydrology Department of the Ministry of Water Resources of Ethiopia, which has a long data record (since 1960) for these stations. However, the latter measurements were made using staff gauge readings twice a day, with many data gaps and discontinuities, particularly at the end of the observation window. The discharge data from 2000-2005 are relatively better and are used to validate the model.

The 2012 discharge data for Dirma catchment (outlet at 12.427194°N, 37.326209°E), collected in the same way as those of Gilgel Abay and Gumara, were used to assess the transferability of the model parameters.

4.5 Calibration and validation

The model calibration and validation were performed at a daily time step, and the hydrological datasets of 2012 and 2011-2012 were used to calibrate the Gilgel Abay and Gumara catchments, respectively. Discharge data of 2000-2005 were used for validation. There are 7 calibration parameters in this model (Table 4.2), and the calibration was performed using the Particle Swarm Optimization (PSO) algorithm. PSO is a population based stochastic optimization technique inspired by social behavior of bird flocking or fish schooling (Kennedy and Eberhart, 1995). The advantages of PSO are that the algorithm is easy to implement and that it is less susceptible to getting trapped in local minima (Scheerlinck et al., 2009). We carried out 50 iterations and 50 repetitions, in total 2500 runs for each catchment to search for the optimal value of the model parameters (Table 4.2) and 30 particles (potential solutions) were used in the PSO. The criterion in the search for the optimal value was to minimize the root mean squared error ($RMSE$) as the objective function, given by:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} (Q_{\mathrm{obs,i}} - Q_{\mathrm{sim,i}})^2}{n}} \tag{4.22}$$

where Q_{obs} is observed discharge [mm/day], Q_{sim} is simulated or modelled discharge [mm/day], and n is the number of data points. The parameter values corresponding to the minimum $RMSE$ were considered as optimum. From the optimal model parameters, the performance of the model was also evaluated using (i) the Nash-Sutcliffe Efficiency (NSE) according to Nash and Sutcliffe (1970), and (ii) the coefficient of determination (R^2).

$$NSE = 1 - \frac{\sum_{i=1}^{n} (Q_{\mathrm{sim,i}} - Q_{\mathrm{obs,i}})^2}{\sum_{i=1}^{n} (\mathrm{Q_{obs,i}} - \overline{Q_{\mathrm{obs}}})^2} \tag{4.23}$$

$$R^2 = \left[\frac{\sum_{i=1}^{n} (\mathrm{Q_{sim,i}} - \overline{Q}_{sim})(\mathrm{Q_{obs,i}} - \overline{Q}_{obs})}{\sqrt{\sum_{i=1}^{n} (\mathrm{Q_{sim,i}} - \overline{Q}_{sim})^2} \sqrt{\sum_{i=1}^{n} (\mathrm{Q_{obs,i}} - \overline{Q}_{obs})^2}} \right]^2 \tag{4.24}$$

where $\overline{Q}_{\mathrm{obs}}$ [mm/day] and $\overline{Q}_{sim}$ [mm/day] are the mean observed and simulated discharges, respectively.

Table 4.2: Model parameters, their ranges, and calibrated values found in 2500 iterations in the PSO calibration

Parameter	Explanation	units	Minimum	Maximum	calibrated values		Average value of both catchments
					Gumara	Gilgel Abay	
β	parameter to account variability of permeability of soil with soil water storage	_	1	3	2.445	2.314	2.380
$k1$	relates discharge and storage for the ground water	_	0.1	2	0.971	1.012	0.992
$K_{s,\mathrm{u}}$	Saturated hydraulic conductivity in the upper soil layer	m/s	0.001	0.1	0.016	0.05	0.033
γ	parameter to account variability of deep percolation with soil water storage	_	0.5	2	1.409	0.9	1.155
λ	coefficient that represents part of catchment that is impermeable	_	0.05	0.5	0.149	0.173	0.161
$\alpha 1$	interflow partitioning coefficient for the steep slope surface	_	0.05	0.8	0.653	0.575	0.614
$\alpha 2$	interflow portioning coefficient for the medium slope surface	_	0.05	0.8	0.065	0.152	0.109

Percent bias (PBIAS) is used as an additional model performance indicator. It measures the average tendency of the simulated data to be larger or smaller than the observations (Gupta et al., 1999). The optimal value of PBIAS is 0, with lower absolute values indicating better model simulation (positive values indicate overestimation, whereas negative values indicate model underestimation bias).

$$PBIAS = \frac{\sum_{i=1}^{n} (Q_{sim,i} - Q_{obs,i})}{\sum_{i=1}^{n} Q_{obs,i}} * 100\% \tag{4.25}$$

The impacts of model parameters on the output of the model when their values are different from the calibrated optimal values were evaluated with respect to the Root Mean Squared Error for Gumara catchment. A sensitivity analysis was made by randomly selecting parameter values in the region of the optimal values obtained from PSO and calculating *RMSE* for each selected value. The applicability of the model to other ungauged catchments outside the study catchments in the Lake Tana basin was also tested using direct parameter transferability.

4.6 Soil and Water Assessment Tool (SWAT) and (FlexB) models as benchmarks for comparison

The two models are used as benchmark models to assess the performance of the model of this study (hereafter named as Wase-Tana model, in favor of the project name that funded this study), which tries to use all available information and considers topography as a good proxy for the variability of most of the catchment characteristics in the Upper Blue Nile basin.

4.6.1 SWAT Model

SWAT is a basin-scale and continuous-time model, used to simulate the quality and quantity of surface and groundwater and predict the environmental impact of land use, land management practices, and climate change (Arnold et al., 1998). The hydrological model is based on the water balance equation

$$SW_t = SW_0 + \sum_{i=1}^{t} (\mathrm{P}_i - Q_i - ET_i - R_i - QR_i)\Delta \mathrm{t} \tag{4.26}$$

where: SW_t is the soil water content [mm] at time *t*, SW_0 is the initial soil water content [mm], Δt is the time step (day) and P_i, Q_i, ET_i, R_i and QR_i respectively are the daily amounts of precipitation, runoff, evapotranspiration, percolation and return flow [mm/day].

In SWAT, a watershed is divided into homogenous hydrologic response units (HRUs) based on elevation, soil, management and land use, whereby a distributed parameter such as hydraulic conductivity is potentially defined for each HRU. Hence, an analysis is confronted with the difficult task of collecting or estimating a large number of input parameters, which are usually not available for regions like the Upper Blue Nile basin. Details of the model can be accessed at the SWAT website (http://swatmodel.tamu.edu).

Automatic calibration and validation of the model was made using SWAT-CUP, which is an interface that has been developed for SWAT automatic calibration and model uncertainty analysis (Abbaspour et al., 2007). Coefficient of determination (R^2) and Nash-Sutcliffe Efficiency (*NSE*) were used as objective functions during the calibration process of the search for the optimal value.

4.6.2 FlexB Model

This model is a lumped conceptual type and it is characterized by three reservoirs as described by Fenicia et al. (2008): the unsaturated soil reservoir (UR), the fast reacting reservoir (FR) and the slow reacting reservoir (SR). The model has eight parameters: a shape parameter for runoff generation β[-], the maximum UR storage S_{fc} [mm], the runoff partitioning coefficient D[-], the maximum percolation rate P_{max} [mm/h], the threshold for potential evaporation L_p [-], the lag times of the transfer functions $\mathrm{N}_{\mathrm{lag}}$ [h], and the timescales of FR and SR: K_f [h] and K_s [h]. Details of the model and the various equations of the model can be found in Fenicia et al. (2008).

Calibration of this model was made using the particle Swarm Optimization (PSO) technique, following similar procedures of the Wase-Tana model calibration algorithm. The same objective function, root mean squared error (RMSE), is also used in the search for the optimal value.

4.7 Results and discussion

4.7.1 The daily hydrograph and model performance

a) Wase-Tana model performance

Figures 4.8 and 4.9 show a comparison of the modeled with the observed discharge data for the two study catchments and for both the calibration and validation periods.

Despite the possible spatial variability of some input data (average soil and rainfall data are considered) and the simplicity of the model, discharge is reasonably well simulated during both the calibration and validation periods. This can be seen from the visual inspection of the hydrographs and from the model performance indicators (Table 4.3).

The Nash-Sutcliffe efficiency of the model is high for both catchments. In the calibration period, *NSE* equals 0.86 for Gumara catchment and 0.84 for Gilgel Abay catchment, while they are 0.78 and 0.7, respectively, during the validation period. Figures 4.8 and 4.9 also show that the model simulates well the overall behavior of the observed streamflow hydrographs. However, an overestimation of the large flood peaks for the Gilgel Abay catchment is found for the validation period. In the calibration period for this catchment, the model errors tend to increase during wetting up periods almost for all the models. Initially, the soils are relatively dry and most of the rainfall during the beginning of the rainy season is not effective to produce runoff in the model as the soil reservoir has to be filled first to generate the faster component of the runoff. However, the value of PBIAS (Table 4.3) in the validation period for Gilgel Abay catchment is large, and in this regard the model has less performance. Besides model uncertainties, the rainfall data quality can also affect the model performance, mainly in the case of the Gilgel Abay catchment. Generally, the modelled discharges appear to be less variable over time than the observations, as shown by the standard deviations in Table 4.3. This is likely due to the fact that data used in the model are averaged over the year, while observed river discharges are highly seasonal. We used average daily rainfall data, average soil data (e.g. porosity, field capacity, and soil depth), average catchment characteristics data (e.g. slope, slope length) to mention some for the model inputs. Hence, this averaged condition may be one source of error such that the model may not exactly mimic extremes like peak discharges.

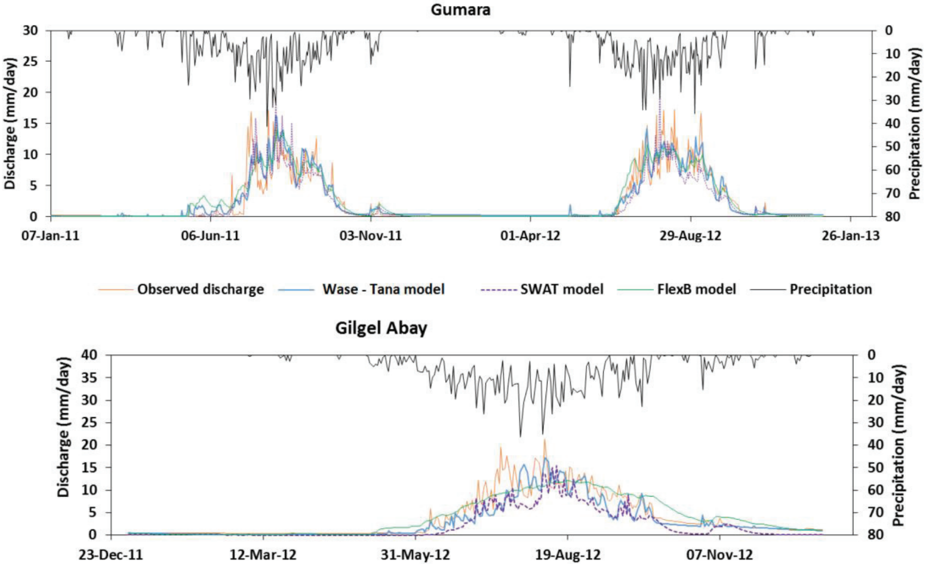

Figure 4.8: comparison of predicted and observed discharge and precipitation of the Gumara and the Gilgel Abay catchments for the calibration period

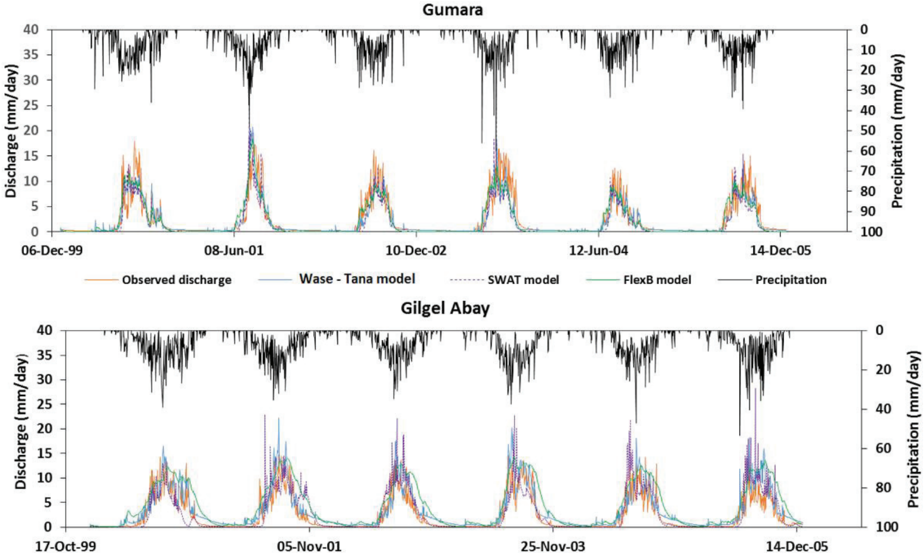

Figure 4.9: predicted and observed discharges and precipitation of the Gumara and the Gilgel Abay catchments for the validation period

Table 4.3: Statistical comparison and model performance of the modelled and observed river discharge (Q) for the two catchments

		Model performance indicators					
		Mean Q [mm/day]	Standard Deviation [mm/day]	RMSE [1] [mm/day]	NSE[2*]	R^2	PBIAS[3]
Observed data		**Gumara**					
	calibration (2011-2012)	2.31	3.79	—	—	—	—
	validation (2000-2005)	2.3	3.75	—	—	—	—
		Gilgel Abay					
	calibration (2012)	3.89	5.05	—	—	—	—
	validation (2000-2005)	2.33	3.4	—	—	—	—
Wase -Tana model		**Gumara**					
	calibration (2011-2012)	2.37	3.56	1.34	0.86	0.86	3.30
	validation (2000-2005)	1.95	3.05	1.37	0.78	0.8	-11.75
		Gilgel Abay					
	calibration (2012)	3.85	4.7	1.85	0.84	0.85	-21.61
	validation (2000-2005)	3.14	3.71	1.67	0.7	0.8	34.06
SWAT model		**Gumara**					
	calibration (2011-2012)	1.91	3.33	1.55	0.77	0.78	-17.50
	validation (2000-2005)	1.62	3.11	1.63	0.72	0.75	-29.48
		Gilgel Abay					
	calibration (2012)	2.02	3.20	1.40	0.60	0.79	-44.01
	validation (2000-2005)	2.45	3.86	2.30	0.55	0.63	5.45
Flex$_B$ model		**Gumara**					
	calibration (2011-2012)	2.43	3.64	1.54	0.82	0.82	5.30
	validation (2000-2005)	2.01	3.35	1.47	0.80	0.81	-12.67
		Gilgel Abay					
	calibration (2012)	3.81	4.03	1.62	0.80	0.84	5.64
	validation (2000-2005)	4.13	4.33	2.15	0.50	0.75	77.67

1. *RMSE* : Root Mean Squared Error as defined in Equation (4.22)
2*. *NSE* : Nash-Sutcliffe Efficiency as defined in Equation (4.23)
3. PBIAS: Percentage Bias as defined in Equation (4.25)

b) Performance in comparison with the benchmark models

For the calibration period, almost all the three models performed well (Table 4.3). However, an appreciable decrease in model performance has been noticed for the validation period in Gilgel Abay catchment for the benchmark models. SWAT is a physically-based complex model, requiring extensive input data which is a challenge for data scare regions like the Upper Blue Nile basin. The model simulations can only be as accurate as the input data. This suggests that the coarser data input used for the model in the study catchments might have affected significantly the calibration and consequently the validation simulations. On the other hand, the likely reason for a decreased performance of the $\mathrm{Flex_B}$ model for the Gilgel Abay catchment is the oversimplification of the catchment heterogeneity, since it is a lumped one and the impact is more when the catchment gets bigger (Gilgel Abay catchment is bigger than Gumara catchment).

A look at the flow duration curves (Fig. 4.10 and Fig. 4.11) indicates the higher uncertainty of both benchmark models (mainly SWAT model) with respect to low flow predictions. In relative terms, the Wase-Tana model offers more flexibility in adapting the model to the catchments based on the validation simulation performances. This can be attributed to the consideration of topography driven landscape heterogeneity analysis and catchment information extraction for the model, which strengthens the hypothesis that topography driven model structure and use of all available information on hydrology based on topography is a good choice for the Upper Blue Nile basin. From a comparison of four model structures on the Upper Heihe in China, Gao et al. (2014) also confirmed that topography-driven model reflects the catchment heterogeneity in a more realistic way.

4.7.2 The hydrograph components and hydrological response of the catchments

This hydrological model (Wase-Tana model) is based on the generation of direct runoff from saturated and impermeable (degraded surfaces and rock outcrops with little or no soil cover) areas, interflow from the soil storage in the root zone layer and baseflow from the deeper layer as groundwater storage. The understanding of the relative importance of these processes on the hydrological response of each catchment is still unknown. The mean annual surface runoff (Q_{se}, sum of Q_{se1} and $QSe2$), interflow or subsurface flow (Q_{ss}) and baseflow (Q_2) components of the total daily hydrograph computed by the model for the calibration and validation periods are given in Table 4.4.

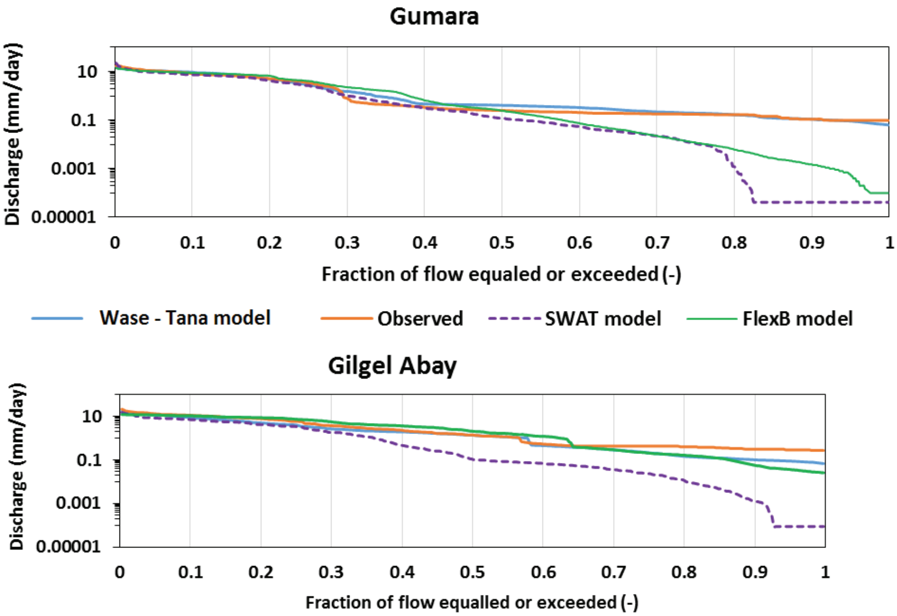

Figure 4.10: Predicted and observed flow duration curves of the Gumara and the Gilgel Abay catchments for the calibration period

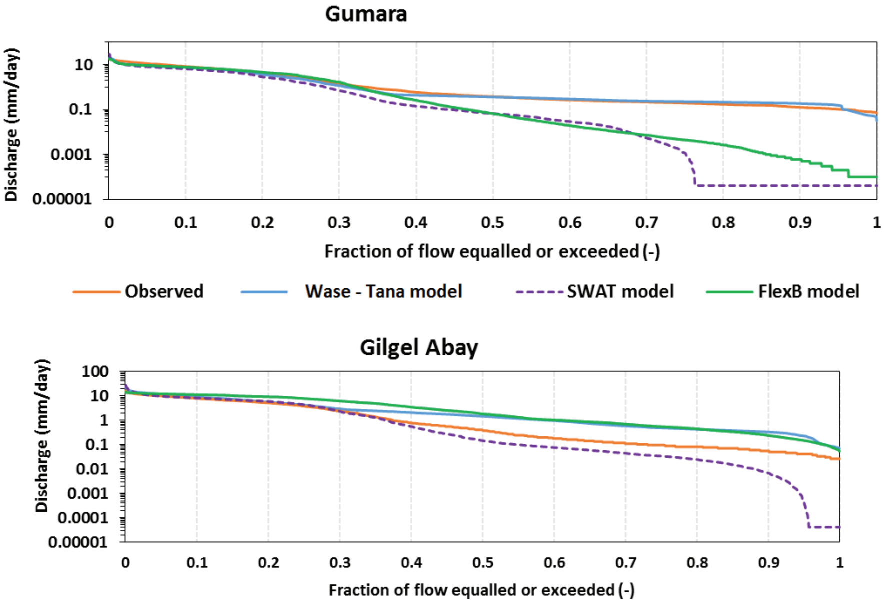

Figure 4.11: Predicted and observed flow duration curves of the Gumara and the Gilgel Abay catchments for the validation period

Table 4.4: Model results on the hydrograph components of the catchments

Runoff components	unit	For the calibration period		For the validation period	
		Gumara	Gilgel Abay	Gumara	Gilgel Abay
Total mean annual runoff predicted (Q_{pr})	mm/year	864	1405	713	1146
Total mean annual runoff observed (Q_{ob})	mm/year	843	1420	841	938
Mean annual surface runoff (Q_{se})	mm/year	161	280	129	234
	% from the total Q_{pr}	19	20	18	20
Mean annual interflow (Q_{ss})	mm/year	574	508	458	369
	% from the total Q_{pr}	66	36	64	32
Mean annual baseflow (Q_2)	mm/year	128	617	126	548
	% from the total Q_{pr}	15	44	18	48

The total mean annual runoff generated by the model is in line with the observations for both catchments in the calibration period (Table 4.4), while an appreciable difference is noticed in the values for the Gilgel Abay catchment in the validation period. The large value of PBIAS (Table 4.3) in the validation period for Gilgel Abay catchment clearly illustrates the appreciable gap between observed and simulated mean annual runoff. . At this time, we could not exactly trace the cause of the problem. But we believe that the cause is the uncertainty with respect to the input data. In fact, the potential and actual evapotranspiration results do not show appreciable differences between the calibration and validation periods (Table 4.5). One of the problems in accurate modelling of the discharge is that precipitation measurements do not cover well the catchments. This is particularly the case for the Gilgel Abay catchment, where the rainfall stations are poorly distributed as most of the meteorological stations lie near the water divides. The calibration results are better, since the data from the recently established precipitation stations (e.g. Durbetie) could be used. There are also doubts on the representativeness of the discharge data used for the validation of the model, because the water level measurements were made manually and twice daily (in the morning and late afternoon), leading to the possibility of missing flash floods at other moments of the day as the stream discharge is very variable. This can be clearly seen from the mean annual observed flows during the calibration and validation periods for Gilgel Abay. The mean annual observed flow in the validation period was found to be much smaller than the corresponding flow during the calibration period (Table 4.4). The closer total mean annual runoff values and the better model performance indicators for the Gumara catchment during the calibration period suggest that the model can perform satisfactorily with better input discharge and precipitation data.

From PBIAS results (Table 4.3), Flex_B model has showed overestimated bias and SWAT model behaved the opposite for both catchments during the calibration period.

Table 4. 5 Potential and actual evapotranspiration for the modelled catchments

	Year	Gilgel Abay	Gumara
Average annual **potential** evapotranspiration estimated by Penman-Monteith method (mm/year)	Calibration period (2012)	1338	1415
	Validation period (2000-2005)	1375	1370
Average annual **actual** evapotranspiration estimated by the model (mm/year)	Calibration period (2011-2012)	705	799
	Validation period (2000-2005)	710	780

Despite the variations in mean annual runoff generated by the Wase-Tana model, the partitioning of the total runoff into the different components (Table 4.4) in each period is almost identical for each catchment, as expected. About 65% of the runoff appears in the form of interflow for the Gumara catchment, and baseflow takes the larger proportion for Gilgel Abay catchment (44 - 48%). Uhlenbrook et al. (2010) obtained the baseflow to be about 32% from similar model study results for Gilgel Abay catchment. Vogel and Kroll (1992) have showed that baseflow is a function of catchment area, and geomorphological, geological and hydrogeological parameters of the catchment have a linear incidence on the discharges. The difference between the baseflow of the two catchments is high, despite their comparable catchment sizes, suggesting rather the different structure, functioning and hydrodynamic properties of both catchments. Hence, the model results reveal that the groundwater in the Gilgel Abay catchment receives more recharge and makes a greater contribution to the river flow. This is in line with Kebede (2013) and Poppe et al. (2013), who showed that the largest part of the Gilgel Abay catchment consists of pumice stones and fractured quaternary basalts with a high infiltration capacity and hydraulic properties, which clarifies the large groundwater potential. In line with this, several big springs exist in the catchment, including one that is used as a source of water supply for Bahir Dar town (Fig. 4.12).

Figure 4.12: One of the springs in Gilgel Abay catchment used as a water supply source for Bahir Dar town, October 2014

The other interesting result is that direct runoff is the smallest fraction of the total runoff for both catchments (18-19% for Gumara and 20% for Gilgel Abay) and almost all peak flow incidences are associated with direct runoff. More than 90% of this direct runoff is found to be from the relatively impermeable (degraded areas, plough pans or rock outcrops with little or no soil cover) surfaces. The calibrated result shows that this type of runoff production area covers 15% of the Gumara and 17% of the Gilgel Abay catchments, respectively. In a similar study, Steenhuis et al. (2009) mention that the rock outcrops occupy 20% of the total catchment area in the Abay (Blue Nile) catchment at the Ethiopia-Sudan border upstream of the Rosaries Dam, which is very similar to the result of Gilgel Abay catchment in this study.

The remaining direct runoff is generated from the flat slopes of the catchments as saturated excess runoff, probably near the valley bottoms. The hillslopes (medium and steep slope source areas in this study) generated almost no direct runoff as saturated excess flow. Similar results were obtained by different researchers in the Blue Nile basin, who identified hillslopes as main recharge areas (Steenhuis et al., 2009, Collick et al., 2009, Tilahun et al., 2013). Our results contribute to the debate on the relative importance of saturated excess runoff versus infiltration excess runoff (Hortonian overland flow) mechanisms in the Upper Blue Nile basin, showing that the rainfall-runoff processes are better represented by the soil reservoir methodology. Yet, further research is necessary that involves rainfall intensity and event-based analysis of hydrographs.

4.7.3 Transferability of model parameters to other ungauged catchments and sensitivity

The sensitivity analysis was performed on model parameters for Gumara catchment with respect to the Root Mean Squared Error. The parameters β, $\alpha 1$ and γ show poor sensitivity for a wide range of values with respect to the local sensitivity analysis. The local sensitivity analysis shows the sensitivity of a variable to the changes in a parameter if all other parameters are kept constant at some value (optimal value in this case). An increase in the value of β beyond 1.4 showed almost no sensitivity, while the model efficiency decreased slightly after an increase in the value of γ from the optimum. This means that there is little confidence in the model's correspondence with these parameters and they can be reduced without appreciable impact on the model (Fenicia et al., 2008). k_1, $K_{s,u}$ and λ are very sensitive parameters in this model and the model performance drops abruptly if the parameters exceed beyond some threshold value (Fig. 4.13).

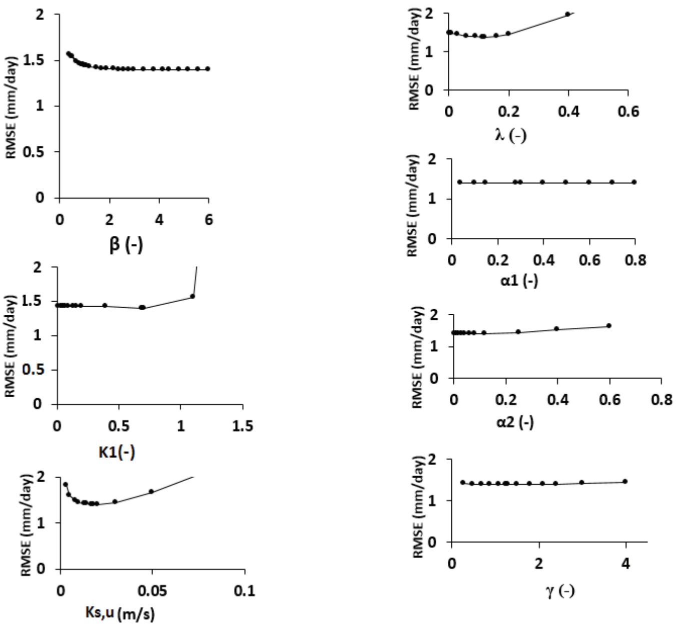

Figure 4.13: Local model parameter sensitivity analysis for Gumara catchment. Parameters are explained in Table 4.2

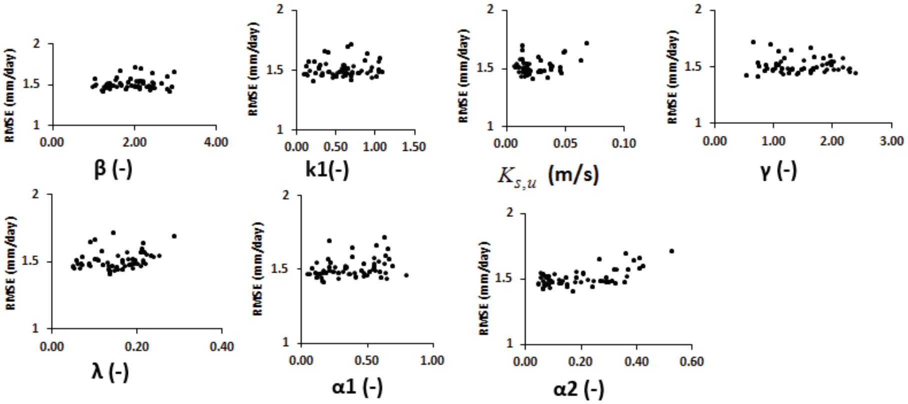

Figure 4.14: Global model parameter sensitivity analysis results for Gumara catchment. Parameters are explained in Table 4.2

The global sensitivity analysis (Fig. 4.14), however, shows interactions among all the input parameters of the model. Although global sensitivity analysis reveals details of the model behavior in a more general sense through random parameter sampling and that the parameters are all sensitive, the local sensitivity analysis indicates that moderate variations of the parameter values for some parameters can still drastically change the model performance.

The model parameter transferability to other ungauged catchments in the basin has been tested by analyzing the variability among the calibrated parameters of both catchments. Table 4.2 shows that the calibrated parameters are nearly identical for both catchments, except for γ and λ, which are related to deep percolation and impermeable fraction of the catchment, respectively. As described above, they affect the baseflow and direct runoff contributions to the total river flow. However, we showed that the contributions of these components to the total runoff are relatively small and γ is poorly sensitive to a wide range of values. Thus the influence of these parameters is expected to be minimal. This is verified by generating flows using the average of the calibrated parameters of the two catchments and analyzing the effect on the model performance indicators (Table 4.5).

Table 4.6: Comparison of model performance between the optimal and average model parameters of the three catchments

catchment		Model performance for the optimal model parameters			Model performance for the average of the optimal model parameters of the two catchments		
		RMSE [mm/day]	*NSE*	R^2	RMSE [mm/day]	*NSE*	R^2
Gumara	Calibration period	1.34	0.86	0.86	1.48	0.84	0.86
	Validation period	1.37	0.78	0.80	1.82	0.76	0.77
Gilgel Abay	Calibration period	1.85	0.84	0.85	1.98	0.83	0.84
	Validation period	1.67	0.70	0.80	1.93	0.68	0.78
Dirma	For the 2012 discharge	-	-	-	1.79	0.58	0.60

The model performance obtained using the average model parameter values is similar to the results found using the optimal model parameters (Table 4.3). To further verify the adaptability of the average calibrated model parameter values outside the study catchments and see the impacts of scale, we applied the average parameter values to another catchment (Dirma catchment in the northern part of the Lake Tana sub-basin, Fig. 4.1b) with an area of 162.6 km^2. Encouraging model efficiency could be obtained, with *NSE* and R^2 values of 0.58 and 0.6 respectively (Table 4.5). This is to be elaborated further in the future, involving more catchments and more years of data.

In general, transferability results showed good performance of the daily runoff model in the two study catchments and an average performance in the test catchment (Dirma catchment). This can be explained by the fact that emphasis was made to incorporate more knowledge in the model structure to increase model realism. We based our model strongly on the soil storage characterization of the soil reservoir in the rainfall-runoff process and representation of the maximum storage of the unsaturated reservoir at the catchment scale, which is closely linked to rooting depth and soil structure and strongly depends on the ecosystem. Transferability of the model has benefited from this in that we were able to derive most of the input data from the test catchments. The consideration of topography driven landscape heterogeneity analysis and catchment information extraction based on topography (slope) for the model is another reason for the better performance of the model transferability. The role of topography in controlling hydrological processes and its linkage to geology, soil characteristics, land cover, and climate through co-evolution have been indicated in different studies (Sivapalan, 2009, Savenije, 2010, Gao et al., 2014). The results suggest the possibility of directly using the average model parameter values for other ungauged catchments in the basin, even though further tests on such catchments is still recommended. However, we believe that this is a useful result for operational management of water resources in this data scarce region.

4.8 Conclusion

In this chapter, a simple conceptual semi-distributed hydrological model was developed and applied to the Gumara and Gilgel Abay catchments in Lake Tana basin to study the runoff processes in the basin. Good quality discharge data were collected through a field campaign using automatic water level recorders with high time resolution. We used the topography and soil texture data of the catchments as the dominant catchment characteristics in the rainfall-runoff process. In the model, a distinction is made between impermeable surfaces (degraded surface or exposed rock with little or no soil cover) and permeable (soil) surfaces, as different types of source areas for runoff production. The permeable surfaces were further divided into three subgroups using topographic criteria such as flat, medium, and steep slope areas. The rainfall-runoff processes were represented by two reservoirs (soil and groundwater reservoirs) and the water balance approach was used to conceptualize the different hydrological processes in each of the two reservoirs. Such a detailed form of modelling, using topography as a dominant landscape characteristics to classify a catchment into different hydrological regimes, has not been applied yet in the Upper Blue Nile, Lake Tana sub-basin.

We demonstrated that the model performs well in simulating river discharges, irrespective of the many uncertainties. Model validation indicated that the Nash–Sutcliffe values for daily discharge were 0.78 and 0.7 for the Gumara and Gilgel Abay catchments, respectively.

We were able to partition the total runoff into a fast component (direct runoff and interflow) and a slow component (baseflow) and estimated the contributions of each component for the catchments. About 65% of the runoff appears in the form of interflow for the Gumara catchment, and baseflow is responsible for the larger proportion of the discharge for the Gilgel Abay catchment (44-48%). Direct runoff generates the lower fraction of runoff components in both catchments (18-19% for the Gumara and, 20% for the Gilgel Abay) and almost all peak flow incidences are associated with direct runoff. More than 90% of this direct runoff is found to be from the relatively impermeable (plough pan or rock outcrops with little or no soil cover) source areas. The hillslopes (medium and steep slope source areas) are recharge areas (sources of interflow and deep percolation) and generated almost no direct runoff as saturated excess flow.

The results of this study, with comparisons to two benchmark models, clearly demonstrate that topography is a key landscape component to consider when analyzing runoff processes in the Upper Blue Nile basin. Generally, runoff in the basin is generated both as infiltration and saturation excess runoff mechanisms. A considerable portion of the landscape in the Upper Blue Nile basin consists of impermeable rock outcrops and hard soil surfaces (15%-17% of the total catchment area as per the results of this study) and they are the sources of most of the direct runoff. This conceptual model, developed to study the runoff processes in the Upper Blue Nile basin, may help to predict river discharge for ungauged catchments for a better operation and management of water resources in the basin, owing to its simplicity and parsimonious nature with respect to parameterization. The runoff processes in the basin are also found to be affected much by the rainfall, as the performance of the model was better for those study catchments where coverage of rainfall stations was good. Hence a better spatial and temporal resolution of rainfall data is required to further improve the model performance and to further enhance the understanding of the runoff processes in the basin. It should however be stated clearly that the results of the model should be considered with great care as there are many sources of errors that could influence the absolute model results. Data are scarce in the study region and may be confronted with uncertainties in their measurement. Soil-based information, for example, is derived from studies previously performed in the region and from literature recommendations. Nevertheless, the outcome of the model is confirmed by other models and by field expertise. As such, the results obtained can be used as indicative for the hydrological processes occurring in the Lake Tana region, and therefore enhances our understanding of the system.

CHAPTER 5

5. Water balance of Lake Tana with floodplain buffering[3]

Abstract

Lakes are very important components of the earth's hydrological cycle, providing a variety of services for humans and ecosystem functioning. For a sustainable use of lakes, a substantial body of knowledge on their water balance is vital. We present here a detailed daily water balance analysis for Lake Tana, the largest lake in Ethiopia and the source of the Blue Nile. Rainfall on the lake is determined by Thiessen polygon procedure, open water evaporation is estimated by the Penman-combination equation and observed inflows for the gauged catchments as well as outflow data at the two lake outlets are directly used. Runoff from ungauged catchments is estimated using a simple rainfall-runoff model and runoff coefficients. Hillslope catchments and floodplains are treated separately, which makes this study unique compared to previous water balance studies. Impact of the floodplain on the lake water balance is analyzed by conducting scenario-based studies.

We found an average yearly abstraction of 420x10^6 m^3 or 6% of river inflows to the lake by the floodplain in 2012 and 2013. Nearly 60% of the inflow to the lake is from the Gilgel Abay River. Simulated lake levels compare well with the observed lake levels ($R^2 = 0.95$) and the water balance can be closed with a closure error of 82 mm/year (3.5% of the total lake inflow). This study demonstrates the importance of floodplains and their influence on the water balance of the lake and the need of incorporating the effects of floodplains and water abstraction for irrigation to improve predictions.

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[3] Adapted from Journal of Hydrology
Dessie, M., Verhoest, N.E.C., Pauwels, V.R.N., Adgo, E., Deckers, J., Poesen, J., Nyssen, J., 2015. Water balance of a lake with floodplain buffering: Lake Tana, Blue Nile Basin, Ethiopia. Journal of Hydrology 522: 174-186. doi:10.1016/j.jhydrol.2014.12.049.

5.1 Introduction

Lakes are very important components of the earth's hydrological cycle, and they contain approximately 90% of the world's available liquid surface freshwater (Shiklomanov, 1993). They provide a wide variety of ecosystem services. Lake Tana, the largest lake in Ethiopia, is a typical example. Bahir Dar (largest city on the lake shore) and the other smaller villages and towns on the lake shore along with the 37 islands in the lake are enjoying the benefits of the lake as means of water transport, recreation, fishery, and sources of water supply for livestock (also for people in some rural towns), irrigated agriculture and industries. Above all, the lake and its basin are the focus of the Ethiopian Government to stimulate economic growth and to reduce poverty through the development of hydropower and a number of irrigation schemes. Being the source of the Blue Nile, this lake also contributes to the livelihoods of people in the lower Nile river basin (Setegn et al., 2009). The Lake Tana basin hosts a vast area of wetlands and floodplains, making it rich in biodiversity and endemic flora and fauna.

Despite the value of lakes outlined above, lakes are particularly vulnerable to stress (Ballatore and Muhandiki, 2002). According to Kira (1997), lakes face five major problems, namely lowering of water level, siltation, acidification, toxic contamination and eutrophication. To cope with such stresses impairing the value of lakes, many management responses have been triggered and a substantial body of knowledge on the processes occurring within lakes, their watersheds, and on lake management in general have been generated (Ballatore and Muhandiki, 2002). Accurate determination of the water balance of lakes is one such instance of knowledge required for the management of lakes.

Several studies have been made to better understand the water balance of Lake Tana on a monthly basis (Kebede et al., 2006; Chebud and Melese, 2009) and on a daily basis (SMEC, 2007; Setegn et al., 2008; Wale et al., 2009; Rientjes et al., 2011). A major difference among the outcomes of these studies originates from the selected procedures they used to estimate inflows to the lake from ungauged catchments of the lake basin. For computational purposes (to indicate how ungauged river inflows to the lake have been quantified during the different water balance studies of the lake), the classification of the basin as gauged and ungauged catchments is made. For the gauged catchments, river discharges have been obtained from the discharge measurements.

Using a mean runoff coefficient of 0.22, computed for the larger Blue Nile basin (Shahin, 1988), Kebede et al. (2006) estimated the lake inflow from the ungauged catchments and showed that most of the lake inflow results from the gauged catchments. Similar results are reported by Chebud and Melese (2009). Studies presented in Chapter 3 and Dessie et al. (2014a) show that the runoff coefficients for the upper catchments of the Lake Tana basin vary between 0.23 and 0.81, but these values are reduced by the downstream floodplain, indicating that runoff coefficients based on an assessment of actual and simultaneous measurements of both rainfall and runoff in the catchments should be used. Based on the principles of regionalization, Wale et al. (2009) and Rientjes et al. (2011) estimate that inflows to the lake from the ungauged catchments are 42% and 30% respectively. They did not differentiate between the hillslopes and the vast ungauged low-lying floodplain catchments. Regionalisation approaches rely on similarity of spatial proximity or on similarity of catchment characteristics (Merz and Blöschl, 2004).

Lake Tana basin is characterized by an extensive floodplain adjacent to the lake and its lowland tributaries (Fig. 5.1 and Fig.3.1). Dessie et al. (2014a) and Chapter 3 in this dissertation show that the floodplain of Lake Tana abstracts a substantial quantity of water from overbank flooding of rivers, rainfall and the percolating groundwater from the upland catchments during the onset of the rainy season (May to Mid of July). This can result in the reduction of river flows to the lake due to abstraction by the extensive lacustrine floodplain on their way to the lake. In a similar study by Kebede et al. (2011), local rainfall and river overflows are the dominant sources of water for the floodplain and the effect of backwater flow from the lake is excluded. They indicated that the major error introduced into the water balance computation is related to evaporative water loss in the floodplains.

A review of the previous water balance studies of the lake reveals that most of these studies ignored this extensive floodplain and its impacts on the water balance of the lake, which is as an important research gap. Significant contribution in this perspective is attributed to Kebede et al. (2011). Floodplains are specific ecosystems, oscillating between terrestrial and aquatic phases (Junk, 1996), having different topography, soils and vegetation patterns. The water balance studies of the lake should address the floodplain hydrology properly and its impacts on the water budgets of the lake. Dawidek and Ferencz (2014) and Kummu et al. (2014) provide a detailed description of the hydrologic regime of the lake–floodplain system to obtain a meaningful assessment of the inflow and outflow contributions by the various hydrological and hydrometeorological components of the system in their water balance studies for a lake-floodplain system in Poland and Cambodia.

SMEC (2007) determined the inflow of the ungauged catchments from the water balance of the Lake Tana using observed lake levels and inflows from the gauged catchments. They obtained lower values of runoff discharges from the ungauged catchments despite rainfall that is comparable with that of other similar gauged catchments; surprisingly, negative inflows were obtained for some months for the combined ungauged areas. How can such discrepancies be explained and what are the underlying causes? It remains necessary to revise the water balance of the lake and to consider the impact of the floodplain to answer such questions based on recently obtained reliable field data and floodplain studies. In this chapter, water balance components of the lake are quantified simulating two scenarios. Scenario 1 attempts to analyze the water balance of the lake omitting the floodplain. This scenario hypothetically removes the floodplain and its buffering effect from the lake system and estimates the water balance of the lake. Scenario 2 deals with the real field situation (the lake basin and the lake-floodplain system) and the effects of the floodplain are included in the analysis. Based on a comparison of the results of both scenarios, the impacts of the floodplain on the water balance of the lake will be evaluated. In this study, another major source of uncertainty for the water balance of the lake (inflows from ungauged catchments) is reduced by increasing the size of coverage of gauged catchments (from about 42% to 60%) through additional reliable discharge measurement stations and by using different approaches to study the impacts of the floodplain. The study also tries to identify parts of the lake catchments that play a major role in the water balance of the lake and that are crucial for the floodplain and its ecosystem services.

5.2 Analysis of components of the water balance

The lake level fluctuations are governed by an Input-Storage-Output process, which can be described by the following water balance model (all terms in $Mm^3\ day^{-1}$):

$$\frac{\Delta S}{\Delta t} = P_{lake} - E_{lake} + Q_{gauged} + Q_{ungauged} - Q_{out} + \varepsilon \qquad (5.1)$$

where $\frac{\Delta S}{\Delta t}$ denotes the change in storage over time, P_{lake} is lake areal rainfall, E_{lake} is the rate of lake evaporation, Q_{gauged} is gauged river inflow, $Q_{ungauged}$ is ungauged river inflow, Q_{out} is the outflow at the Blue Nile River and at the tunnel to the hydropower station, and ε represents the uncertainties in the water balance arising from errors in the data and other terms, such as net groundwater flux or minor abstractions, which usually cannot be accounted for directly.

Isotope geochemical studies of groundwater in the vicinity of the Lake Tana by Kebede et al. (2005) suggested little evidence of leakage from the lake to adjacent aquifers but do not preclude groundwater inflow to the lake (particularly along the rocky southern shore). Similar results are reported by Kebede et al. (2011). Chebud and Melese (2009) studied the groundwater interactions using numeric groundwater modeling and results indicate that lake leakage is unlikely. In light of this, exchange of water between the lake and the groundwater system is ignored and the model (Equation 5.1) assumes the value of ε to be zero. In the following subsections, a description of the procedures to determine the water balance components is presented.

5.2.1 Estimation of rainfall and evaporation on the lake

There are 40 meteorological stations within and near the Lake Tana basin (Fig.5.1 and Fig. 2.11), most of which only record rainfall depth and air temperature. Even though the number of stations seems reasonable, the data series were not complete for some of the stations. Daily measurements from six precipitation stations, located at the lake shore (Bahir Dar, Gorgora, Dengel Ber, and Zegie), at the island of the lake (Dek Estifanos) and close to the lake (Maksegnit), were used to calculate areal rainfall on the lake by the Thiessen Polygon method.

For estimating the lake water evaporation depth, daily maximum and minimum air temperature data from the above 6 stations is used, whilst wind speed, relative air humidity and sunshine hours are collected from Bahir Dar meteorological station.

The daily evaporation depth was estimated by the Penman-combination method (Maidment, 1993), which is widely applied as a standard method in water resources engineering. This technique combines the energy balance and the water vapour transfer methods to compute the evaporation of open water surfaces using daily sunshine hours, air temperature, air humidity and wind speed data.

5.2.2 Runoff from gauged catchments

There are more than 40 tributaries draining into Lake Tana, although the major ones are Gilgel Abay, Gumara, Rib and Megech Rivers (Fig. 5.1).

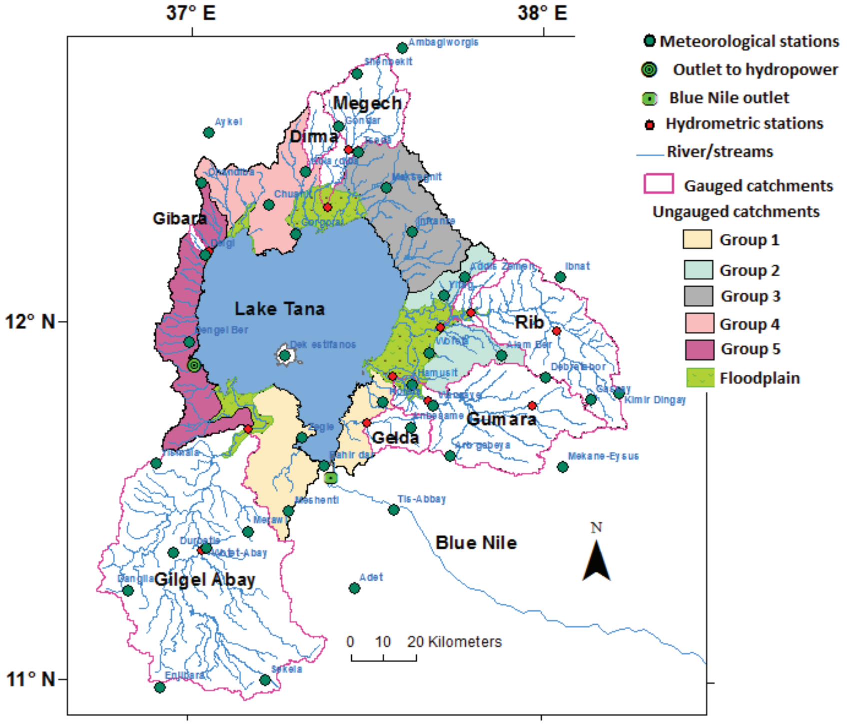

Figure 5.1: Gauged and ungauged catchments in the Lake Tana Basin. Runoff from the groups of ungauged catchments was predicted based on calibrated model parameters of observed runoff data from Gelda for Group 1, from Rib for Group 2, from Megech for Group 3, from Dirma for Group 4, and from Gibara for Group 5.

For computational purposes, the basin was divided into gauged and ungauged areas (see Fig. 5.1). The floodplain area (most part ungauged) was also considered separately (see details in Section 5.2.3).

In this study, a best estimate of the daily runoff flowing into the lake from the gauged catchments has been derived for the period 2012 and 2013 using measured water levels of the rivers. The field measurements have been carried out on different water level monitoring stations in the basin (those used in this chapter are indicated in Fig. 5.1), which has increased the gauged catchment area coverage to 60%. Three of the monitoring stations were set in the floodplain to study the impacts of the floodplain on the discharges of Gumara, Rib and Megech Rivers, as most of the floodplain is located in the downstream reaches of these rivers (see details in Chapter 3). The water level measurements and discharge computations from the water levels using rating curves were discussed in the preceding chapters.

5.2.3 Runoff from ungauged catchments

The runoff from the ungauged parts of the catchments was estimated using a conceptual hydrological model and a runoff coefficient approach. The latter approach estimates the runoff from the ungauged catchments as a product of the selected runoff coefficient and the rainfall for that catchment. Earlier water balance studies of the lake used either of the above two approaches to estimate the runoff from the ungauged catchments. In the previous studies that used the runoff approach, the same runoff coefficient was applied both for the hillslope catchments and the floodplain. Likewise, the conceptual hydrological models used by the other researchers during the water balance studies of the lake hardly made a distinction between the hillslope and floodplain hydrological processes (they were treated as one in the system representation). In this study, both methods were considered. However, the methods are applied differently. In line with the previous studies, hydrological models were used for ungauged catchment rivers that drain to the lake with no or minimal influence of the floodplain on their way to the lake. The conceptual hydrological model (Chapter 4), which is based on physical characteristic of the ungauged catchments, is assumed to better represent their hydrological processes. However, we preferred not to use this model for the floodplain and hillslope catchments (whose runoff on the way to the lake is affected by the floodplain) as the hydrological processes in the floodplain are relatively complex. The runoff estimation of the ungauged floodplain and the hillslope catchments that are affected by the floodplain as the rivers flow across the floodplain are made using the runoff coefficient approach. The runoff coefficients were determined based on discharge measurements from three discharge monitoring stations in the floodplain (Chapter 3). Hence, for scenario 1 (omitting the floodplain and its effects) the total ungauged catchment runoff was determined using the conceptual hydrological model developed in Chapter 4.

Scenario 2 includes ungauged catchments that can be floodplains or hillslopes with or without the influence of the floodplain. The flows of Gumara and Rib Rivers in the east, Megech and Dirma in the north and some of the adjacent catchments in the northern part of the Lake Tana basin end up in the floodplain, whereby their runoff to the lake is influenced by the floodplain. There is also a relatively smaller floodplain at the joining of Gilgel Abay to the lake at the southern shore. The ungauged runoff from these floodplains and the hillslope catchments that flow across (or end up) the floodplains were estimated from the runoff coefficients (Table 5.1) obtained from measurement stations in the floodplain (simply by multiplying the corresponding runoff coefficient by the rainfall amount for that catchment or floodplain), since the direct application of models is unreliable because of the impact of the floodplain. Therefore, for scenario 2 (representing the real world), both the conceptual hydrological model and the runoff coefficient approaches were used.

5.2.4 The hydrological model

The hydrological model described in Chapter 4 and Dessie et al. (2014b), developed and tested in Lake Tana basin, has been selected to quantify the runoff from all the ungauged catchments under scenario 1, and from the hillslope ungauged catchments that directly flow to the lake (not affected by the floodplain) under scenario 2. The model is based on the water balance approach, in which the catchment was first divided into soil and impermeable surfaces (details are provided in Chapter 4). Observed discharge data at Gelda, Rib at edge of floodplain, Megech, Dirma and Gibara stations are used in the modeling approach to estimate the runoff for the other ungauged catchments in the basin (Fig. 5.1).

Table 5.1: Characteristics of the ungauged catchments (including the floodplain), the runoff which are influenced by the floodplain on the way to the lake, and the runoff coefficients used to estimate their corresponding runoff depths.

Location	catchment area (km^2)	Runoff coefficients for stations in the floodplain		Average runoff coefficient
		year 2012	year 2013	
Gumara catchment	81.7	0.65	0.53	0.59
Rib Catchment	950.1	0.22	0.2	0.21
North of Lake Tana basin (including Megech, Dirma and adjacent catchments)	1170.3	0.37	0.11	0.24
Gilgel Abay and Adjacent catchments	336.5	0.61	0.5	0.56

a) Model calibration and validation

The model calibration and validation were performed at a daily time step, and the hydrological datasets of years 2012 and 2013 were used to calibrate and validate the five catchments (Gelda, Rib at edge of floodplain, Megech, Dirma and Gibara), which are selected to be representative of the ungauged catchment groups for direct transfer of calibrated model parameters based on the assumption that catchments which are close to each other will likely have a similar runoff regime. There are 7 calibration parameters as described in Chapter 4, Dessie et al. (2014b) and Table 5.2 and the calibration was performed using the Particle Swarm Optimization (PSO) algorithm.

The criterion in the search for the optimal value was to minimize the root mean squared error (RMSE). The parameter values corresponding to the minimum RMSE were considered as optimum. From the optimal model parameters, the performance of the model was also evaluated using (i) the Nash-Sutcliffe Efficiency (NSE) according to Nash and Sutcliffe (1970), and (ii) the coefficient of determination (R^2).

Table 5.2: Model parameters and calibrated values found in 2500 iterations in the Particle Swarm Optimisation (PSO) calibration

Parameter	Explanation	units	calibrated values				
			Gelda	Rib Abobahir	Megech	Dirma	Gibara
β	parameter to account variability of permeability of soil with soil water storage	_	0.5	2.34	2.34	2.36	0.51
k1	relates discharge and storage for the ground water	_	1.05	0.59	0.52	1.03	1.00
$K_{s,u}$	Saturated hydraulic conductivity in the upper soil layer	m/s	0.016	0.01	0.01	0.02	0.016
γ	parameter to account variability of deep percolation with soil water storage	_	1.4	1.5	1.9	1.08	1.4
λ	fraction of catchment that is impermeable	_	0.25	0.15	0.1	0.25	0.3
$\alpha1$	interflow partitioning coefficient for the steep slope surface	_	0.65	0.54	0.54	0.51	0.65
$\alpha2$	Interflow partitioning coefficient for the medium slope surface	_	0.06	0.12	0.12	0.12	0.06

b) Model parameter transfer to the ungauged catchments

There can be different methods to transfer the calibrated model parameters to the ungauged catchments for the runoff estimation. Wale et al. (2009) and Rientjes et al. (2011) used regionalization approaches when estimating the runoff to Lake Tana from the ungauged catchments. Critical to the results of the regionalization procedure in their works is the low number of gauged catchments as they used only six catchments for the correlations between physical catchment characteristics and model parameters. We note that in most regionalisation studies a much larger set of gauged catchments is used (Merz and Blösch, 2004; Young, 2006; Deckers at al., 2010). Haberlandt et al. (2001) support the assumption of large variability and a clear range of different conditions within the catchments to consider regionalisation. In this study, calibrated model parameters are directly transferred to the ungauged catchments based on the assumption that catchments which are close to each other will likely have a similar runoff regime. For this purpose, the ungauged part of the Lake Tana basin (excluding the floodplain) is classified into five groups based on their proximity to the gauged catchments for ease of the direct transfer of calibrated model parameters to the ungauged catchments (Fig. 5.1). The group 1 ungauged catchments cover an area of 901.6 km^2 and consists of the downstream reaches of the Gelda and Gilgel Abay Rivers on both sides of the natural outlet of the lake as well as some minor adjacent catchments. The runoff discharge from this part of the ungauged catchment was computed based on the calibrated model parameters of the gauged Gelda catchment. Similar procedures were followed for the other ungauged catchments such that calibrated model parameters of the gauged catchment of Rib could be used for ungauged catchment Group 2, Megech for Group 3, Dirma for Group 4 and Gibara for catchment Group 5.

5.2.5 Outflow, lake levels and water level-area-volume relationships

After the Tana Beles Hydropower Scheme was made operational (May 2010), outflow from Lake Tana occurs both by the Blue Nile River, which starts at Chara Chara weir near the city of Bahir Dar, and by a tunnel hydropower outlet (Tana Beles) on the southwestern side of the lake (Fig. 5.1). Daily observation records of discharges are available on both outlets (from Ministry of Water, Irrigation & Energy and Tana Beles Hydroelectric Power Plant, Ethiopia) and are directly used in the present water balance and lake level simulation studies. We obtained daily lake water level data at Bahir Dar and Kunzila stations (Tana Beles Hydropower outlet) for the years 2012 and 2013. On average, the water level observations at Kunzila station are 15 cm higher than the corresponding water levels at Bahir Dar station (likely because of variations in the hydrostatic pressure within the lake). Average lake levels from the two stations were taken. The zero level of the staff gauge near Bahir Dar equals 1783.515 m a.s.l. The average daily water level over the two years period (2012 and 2013) varied from 1785.6 m a.s.l. to a peak value of 1787.8 m a.s.l.

The relationships between water surface elevation (Z), area (A), and volume (V) of the lake were calculated using the bathymetric data of the lake. Several historical documents report on bathymetric surveys of the lake. The oldest one was published by Morandini (1940), followed by Studio Pietrangelli (1990). A bathymetric survey by the Institute for Geoinformation Science and Earth Observation (ITC) (Kaba, 2007) was also made, following a 5-km traverse route that covered a total path of 835 km and 4424 sample points. A detailed and wide in scope study of the bathymetric survey of Lake Tana was conducted by Omega Development Service Plc in 2012, promoted by the Ethiopian Ministry of Water, Irrigation and Energy. This recent study is very extensive with fine grids of 1 km (Primary Transect) by 3 km (Secondary Transect) spacing and are used in this chapter. Figure 5.2 depicts a plot of these data.

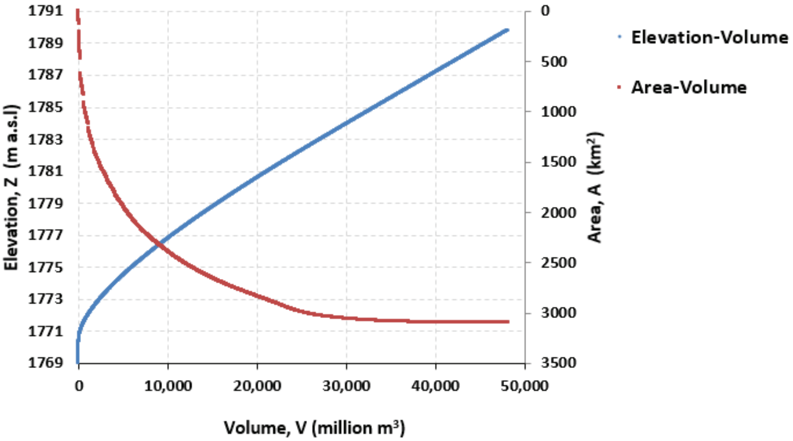

Figure 5.2: Elevation (Z) – volume (V) and area (A) – volume (V) plots for Lake Tana

5.2.6 Water abstraction for irrigation

More than 80% of the population living in the Lake Tana basin is dependent on agriculture. The agricultural production for most of the farmers in the basin is rain-fed. Smallholder irrigated agriculture is also quite common, especially along the Gumara, Rib and Megech river courses in the floodplain by tapping river water using pumps.

Based on Abbay Basin Master Plan studies, BCEOM (1998b) has identified a net irrigation area of 121,260 ha in the Lake Tana basin (10% of the basin area, excluding the lake), while recent studies by Wale et al. (2013) increase the figure to 11%. Currently, the Koga irrigation project in the basin is operational, which is targeted to develop more than

6,000 ha of modern farmer managed irrigation. For the realistic water balance assessment of the lake, it is necessary to quantify such water abstractions by irrigation in the ungauged part of the basin. For the gauged catchments, the discharge monitoring stations will account any upstream water abstractions.

To estimate such water abstractions, 7 mm/day total crop water requirement for the basin is considered (Wale et al., 2013) and the effective irrigation time to be from October-May.

5.3 Results

5.3.1 Lake evaporation

Average daily evaporation depth from the lake, based on constant albedo of 0.08 and average monthly measured sunshine hours (taken as Option 1) for the period 2012-2013, varied from a minimum of 3.21 mm/day in December to a maximum of 8.04 mm/day in April (Fig.5.4b, Option 1), resulting in an average annual evaporation of 1835 mm. This value is higher than that estimated in previous studies. Moreover, the smallest evaporation is encountered in December, while the recent available pan and pitche atmometer evaporation data for Bahir Dar (Fig.5.4a) show that the evaporation during the rainy phase is the smallest (some days in the rainy season have evaporation rates less than 1 mm/day).

Analysis results by Alebachew (2009) using satellite data and in situ measurements for Lake Tana reveals a clear seasonal variability of albedo on the lake (Fig. 5.3). This is due to the fact that the rainy season is associated with flash floods entering into the lake thereby increasing the suspended sediments and resulting in a sharp increase on the reflectance of the water surface. Hence, using a constant albedo of 0.08 for all the seasons overestimates the evaporation for the rainy season. Moreover, use of average measured monthly sunshine hours has shadowed the fact that the actual measured daily sunshine hours are much lower in the rainy season for some days than the average monthly sunshine hours. Accordingly, the Penman evaporation estimations were further investigated (taken as Option 2) by considering the actual daily sunshine hours (instead of the average monthly sunshine hours) and by considering an albedo of 0.16 (Fig. 5.4) for the rainy season (June-September).

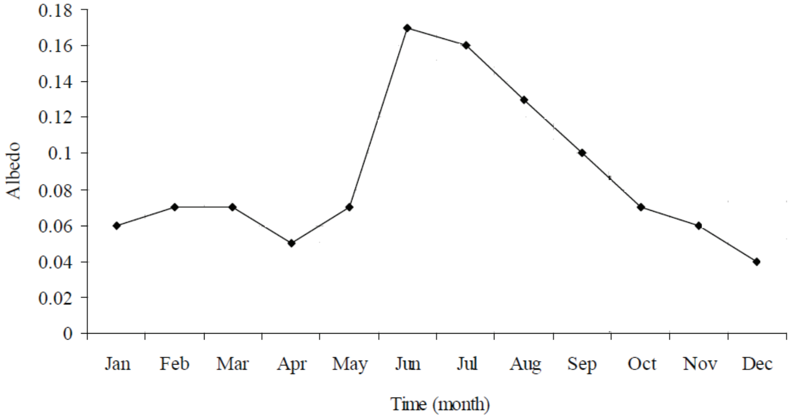

Figure 5.3: Annual cycle of albedo for Lake Tana (adapted from Alebachew, 2009)

The evaporation estimates of the lake were compared with the recent available pan and atmometer evaporation measurements of Bahir Dar (Fig. 5.4c).

Mean annual measured pan and atmometer evaporations for the years 2005 and 2006 at Bahir Dar station are 1945 mm and 2160 mm, respectively (Fig. 5.4a). Penman estimations of the lake evaporation for the years 2012 and 2013, based on Option 2 (measured daily sunshine hours and a rainy season albedo of 0.16), yielded an average annual value of 1789 mm (Fig. 5.4b), 46 mm less than that estimated using Option 1 (constant albedo and average monthly measured sunshine hours). Significant improvement in the second option of Penman evaporation estimation is observed and the estimates could simulate the measured pan and atmometer evaporation better, respecting the time variations considered in the comparison. Minimum evaporation was observed in the rainy season for both cases (0.9 mm/day for the pan and atmometer measurement, 1.72 mm/day for Option 2). Mean annual measured evaporation is greater than the value obtained using the Penman method, estimated to measured coefficients being 0.83 for the atmometer and 0.92 for the pan. Generally, the evaporation from the pan and atmometer is expected to be high, owing to the oasis effect especially during the dry seasons (Fig. 5.4c). Option 2 is considered as better estimate and it is used for the water balance analysis.

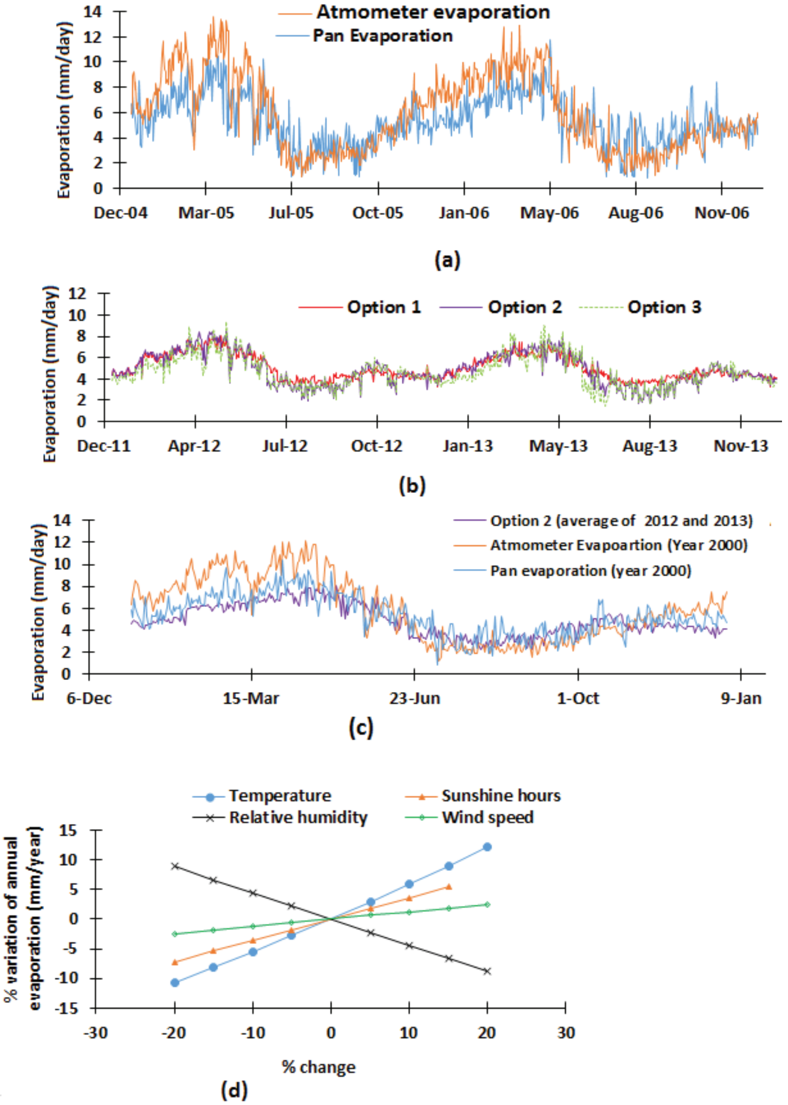

Figure 5.4: Evaporation showing (a) the 2005 and 2006 pan and atmometer evaporation for Bahir Dar, (b) the Penman derived evaporation results for Lake Tana under Option1, Option 2 and Option 3 in 2012 and 2013, (c) comparison of measured and Penman based evaporation rates (Option 2) on annual basis and (d) sensitivity analysis of annual evaporation on the lake by the Penman method for a change in different meteorological variables.

The lake evaporation estimated in this study is still higher than that estimated in previous studies. Despite variations in some of the assumptions and the time of the study, most of the previous studies used air temperature data of Bahir Dar and Gondar stations for the lake evaporation calculations. In this study, 5 additional stations for air temperature are considered (including the recently established Dengel Ber meteorological station at the western lake shore, a relatively warmer part of the basin) for the evaporation computation. For comparison purposes, evaporation estimation using only Bahir Dar meteorological data for the years 2012 and 2013 (Option 3 in Fig. 5.4b) was made and a mean annual evaporation rate of 1709 mm was obtained (Fig. 5.4b, Option 3), close to one of the previous study estimates (Wale et. al, 2009).

Coulomb et al. (2011) found an annual evaporation rate of 1870 mm for Lake Ziway in Ethiopia using a similar method (Penman method). They used the meteorological data of Ziway town (located on the lake's western shore) having almost similar meteorological conditions with Bahir Dar.

It is obvious that estimation of evaporation from the lake is not a simple matter as it is affected by various factors, notably the climate and physiography of the water body and its surroundings. Given the data constraints, sometimes, it becomes necessary to approximate such data. Due to the absence of water surface temperature data, for example, the air temperature data was used in this lake evaporation estimation (also presumably in the other previous studies). Hence, it is important to analyze the sensitivity of temperature changes (Fig. 5.4d) and how it affects the stability of the resulting evaporation estimates. As we can see from Fig. 5.4d, evaporation is quite sensitive to temperature.

5.3.2 The hydrological model performance and uncertainty

The model performance results (Table 5.3) show that the Nash-Sutcliffe Efficiency (NSE) varies from 0.56 to 0.74 for the calibration period and from 0.53 to 0.81 for the validation period in the selected catchments. The simulated and observed runoff discharges from the catchments for the calibration period are depicted in Fig. 5.5. The hydrograph inspections (Fig. 5.5) revealed that the mismatch of observed and modelled discharges generated by the large precipitation events is high for the relatively smaller catchments (Dirma and

Gibara), suggesting the sensitivity of the model to catchment sizes and its uncertainty for smaller catchments.

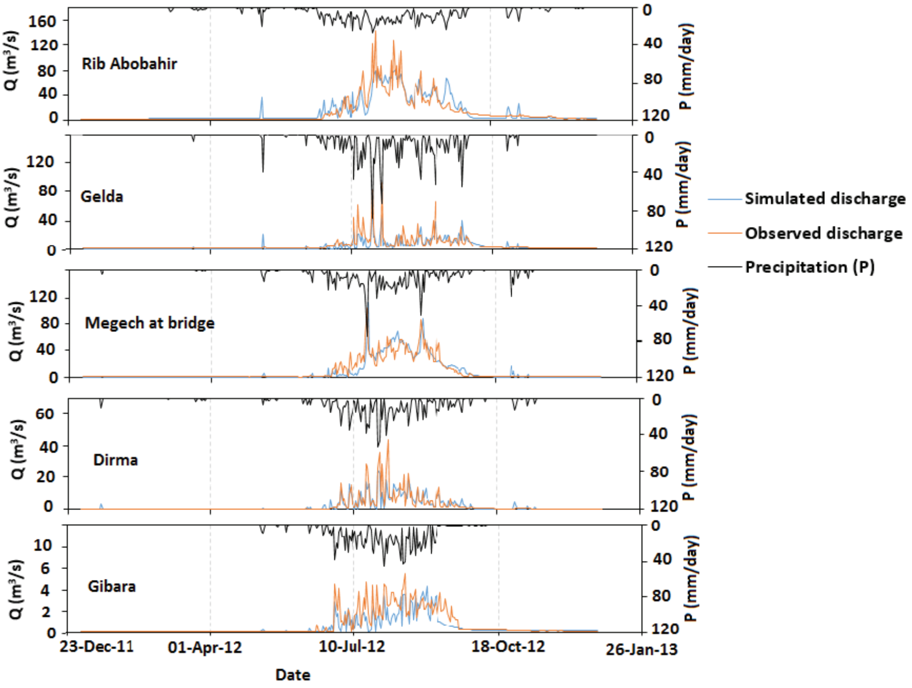

Figure 5.5: Comparison of simulated and observed runoff discharges of Gelda, Rib Abobahir, Megech at bridge, Dirma and Gibara Rivers for the calibration period

On the basis of the identified optimal parameter sets (Table 5.2), we note that some parameters have a relatively large value range across the five catchments. This indicates the possible variability of the Lake Tana basin with respect to climatic, topographic and physiographic properties and the role of grouping the basin into representative classes to transfer the model parameters. It is also important to note the uncertainty of the gauge readings and rating curves for the different stations as a possible cause for variation of discharges between the watersheds.

Table 5.3: Model performance results of the modelled catchments

Model performance indicators		Gelda	Rib Abobahir	Megech	Dirma	Gibara
Calibration (2012)	R^2	0.56	0.75	0.76	0.67	0.64
	RMSE (m^3/s)	6.82	10.9	8.04	3.02	0.71
	NSE	0.55	0.74	0.74	0.66	0.6
Validation (2013)	R^2	0.53	0.80	0.82	0.61	0.58
	RMSE (m^3/s)	7.00	13.62	5.55	1.48	0.51
	NSE	0.53	0.78	0.81	0.52	0.54

Wagener et al. (2001) suggested the need to find a balance between model performance, parameter identifiability, and model structure suitability during the development and application of hydrological models. Over-parameterization and associated equifinality problems can be important causes of output uncertainty. Hence, the model structure in this modelling approach is made parsimonious as much as possible and the number of parameters have been limited to seven. Moreover, we conducted a regional parameter sensitivity analysis to assess the importance of each parameter. Fig. 5.6 depicts the result of the analysis for one of the catchments (Megech catchment). The scatterplots (Fig. 5.6) obtained through random parameter value inputs to the model show that the model performance was affected as the model parameter values varied. Hence, the sensitivity analysis indicates that the model parameters are plausible and identifiable. However, it is difficult to identify which parameter is more sensitive to the other as the scatterplots have almost similar patterns. In this regard, local parameter sensitivity analysis is better than regional sensitivity analysis as shown in Chapter 4 and Dessie et al. (2014b).

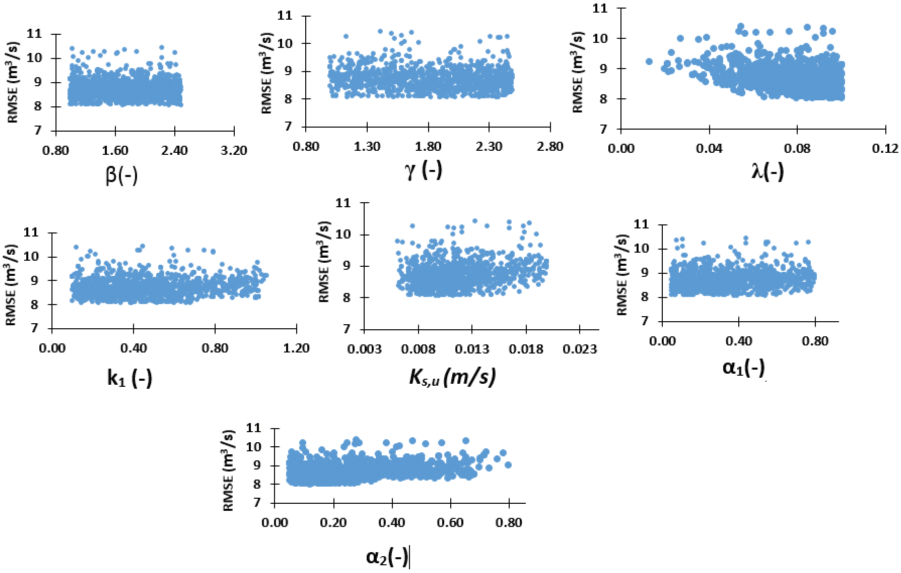

Figure 5.6: Global model parameter sensitivity analysis results for Megech catchment

5.3.3 River inflows

The analysis of river inflows for the years 2012 and 2013 revealed that Lake Tana received an average yearly runoff of 5.61x10^9 m^3 from gauged and 1.22x10^9 m^3 from ungauged catchments (Table 5.4), disregarding the water abstraction by irrigation in the ungauged catchments. More importantly, 0.42x10^9 m^3 of water (Table 5.4) does not reach the lake. Most of the abstraction (about 50% of the total) takes place by the floodplain (via runoff transmission losses) following the downstream reaches of the Rib River. Floodplains at some reaches of the Gumara River and the southern shore of the lake are exceptions and there is runoff contribution from these floodplains (Table 5.4 and 5.5) as indicated by the presence of many springs in these areas.

Table 5.4: Hydrological characteristics of gauged rivers in Lake Tana basin

Gauged river inflows					
River	Catchment area (km^2)	Station	Average discharge (x 10^6 m^3/year)	Abstraction by the floodplain (x 10^6 m^3/year)	Discharge into the lake (x 10^6 m^3/year)
Gumara	1236	Wanzaye Station at edge of floodplain	1121	-69	1190
	1351	Lower Gumara station (in the floodplain)	1190		
Rib	1174	Rib Station at edge of floodplain	442	69	373
	1308	Rib station (in the floodplain)	373		
Megech	514	Megech Station (upstream of floodplain)	233	37	196
	631	Megech Station (in the floodplain)	196		
Dirma	163	Koladiba Station (upstream of floodplain)	46	—	46
Gibara	23	Delgi Station (Upstream of floodplain)	16	—	16
Gelda	217	Gelda Station (upstream of floodplain)	166	—	166
Gilgel Abay	3598	Chimba Station (at edge of floodplain)	3622	—	3622

Table 5.5: Hydrological characteristics of ungauged catchment groups in Lake Tana basin and summary of inflows to the lake and abstractions by the floodplain

Ungauged river inflows				
Ungauged catchment group	Area (km^2)	Average discharge at entrance to floodplain (x 10^6 m^3/year)	Abstraction by the floodplain (x 10^6 m^3/year)	Discharge into the lake (x 10^6 m^3/year)
1	963	446	-53	499
2	776	353	227	126
3	1022	319	-3	321
4	703	143	93	50
5	613	346	119	226

Summary of inflows and floodplain abstractions

Total average yearly river inflows to the lake from gauged catchments = 5608x10^6 m^3 (Table 5.4)

Total average yearly river inflows to the lake from ungauged catchments = 1223x10^6 m^3

Total yearly net abstractions by the floodplain = 420x10^6 m^3

Kebede et al. (2011) found the annual runoff from the ungauged catchments and the groundwater to be 538 mm, which is nearly an exact match with scenario 1 result (530 mm) for the ungauged catchments of this study. However, it should be noted that there is some variation in the size of the ungauged catchments and rainfall corresponding to variations in the time of study. Another surprising incidence between both studies is that the water flow reduction to the lake by the floodplain is quite similar, 0.454×10^9 m^3 evaporative water loss by the flood plain in Kebede et al. (2011) and 0.42×10^9 m^3 water abstraction by the floodplain in this study.

Further analysis of the river inflows to the lake shows that 58% of the inflow to the lake is generated from the southern part of the catchment (Table 5.6), which covers about 38% of the total catchment area of the lake. With respect to the contribution of specific inflow (per km^2 of catchment area) to the lake, the western and northern catchments of the lake are less important.

Table 5.6: Runoff inflows to Lake Tana for different sub-catchments

Lake Tana catchment divisions	Major Rivers	Catchment area (km^2)	Average annual rainfall (mm)	Inflow to the lake (mm)	Inflow to the lake ($\times 10^6$ m^3)	Inflow to the lake from the total (%)
Southern catchment	Gilgel Abay	4507	1660	880	3961.08	58
Eastern catchment	Gelda, Gumara and Rib	4182	1470	490	2044.76	30
Northern catchment	Garno, Arno, Gabi Kura, Megech, Dirma	2651	1140	260	689.24	10
Western catchment	more than 20 smaller streams	660	1035	210	136.41	2

5.3.4 Water abstraction for irrigation

The irrigation water consumption estimates for the ungauged catchments in the Lake Tana basin (Table 5.7) show that currently about 133×10^6 m^3 of water is abstracted from these areas. This results in a corresponding annual lake level reduction as high as 43 mm. For scenario 1 (hypothetically omitting the floodplain), the lake level reduction becomes 35 mm.

Table 5.7: Quantification of water abstraction by irrigation in the ungauged catchments in the Lake Tana basin

Description	Quantity		unit	Remark
	Scenario 1	Scenario 2		
Lake Tan basin area (excluding the lake area)	11069	12000	km^2	Total basin area including the lake is about 15077 km^2 and the floodplain is ca. 931km^2 (Chapter 3 and Dessie et al., 2014a)
Ungauged catchment area in the basin	3869	4800	km^2	The gauged catchment area has increased to 60% in the basin
Potentially irrigable area in the Lake Tana basin	1218	1320	km^2	11% of the basin area (Wale et al., 2013)
Potentially irrigable area in the ungauged catchments in the Lake Tana basin	426	528	km^2	40% of the basin is ungauged
Currently irrigated land for the ungauged catchments in the basin	64	79	km^2	We assumed currently 15% of the potential is irrigated in the basin
Daily irrigation demand per km^2 irrigated area	7000	7000	m^3	Considering total irrigation demand as 7mm/day (Wale et al.,2013)
Annual water abstraction by irrigation in the ungauged catchments of Lake Tana basin	107 x 10^6	133 x 10^6	m^3	Considering October to May as the irrigation period (excluding the rainy season)
Annual flow reduction on the lake because of the irrigation in the ungauged catchments	35	42	mm	Lake area of 3077 km^2 is taken (Dessie et al., 2014a)

5.3.5 The water balance terms

The water balance components of the lake are the direct rainfall over the lake surface (P_{lake}), inflow from the gauged rivers (Q_{gauged}), inflow from unmonitored rivers ($Q_{ungauged}$), outflow from the lake (Q_{out}), lake evaporation (E_{lake}), and the change in water balance or the closure term, as given in equation (5.1). The results of the annual input and output water fluxes of the lake for both scenarios are indicated in Table 5.8**.**

Table 5.8: Average annual water balance terms of Lake Tana (years 2012 and 2013).

Water balance terms	Scenario 1		Scenario 2	
	mm	10^6 m³	mm	10^6 m³
Lake areal rainfall	1330	4129.0	1330	4129.0
Gauged river inflow	1819	5645.5	1807	5608.2
Ungauged river inflow	530	1645.3	394	1223.3
Lake evaporation	-1789	-5547.3	-1789	-5547.3
Outflow from the lake	-1618	-5022.9	-1618	-5022.9
Water abstraction by irrigation	-35	-108	-42	-134
Closure term	238	741.6	82	256.3

The annual estimated precipitation depth over the lake is 1330 mm and the evaporation loss is about 1789 mm. For scenario 1, where the total catchment area draining into the lake is smaller than the actual drainage area of the lake by about 931 km^2 because of omitting the floodplain, the total inflow from the rivers into the lake is 2349 mm. This is greater than the inflow under scenario 2 (2201 mm), showing that an appreciable volume of river inflows to the lake are abstracted by the floodplain (148 mm or 6 %).

5.3.6 Lake level simulations

After determining the daily water balance terms, a water balance model is developed to simulate the lake level based on Equation (10).

$$V_{lake}(t) = V_{lake}(t-1) + \frac{\Delta S}{\Delta t} \tag{5.2}$$

where $V_{lake}(t)$ is total lake volume at day t, $V_{lake}(t-1)$ is lake volume at day $t-1$ and $\frac{\Delta S}{\Delta t}$ is change in lake storage during the time step Δt.

The results of lake level simulations (Fig. 5.7) indicate a good match with the observed lake levels for both scenarios, although larger deviations are observed for scenario 1 during the end of the simulation period. The lake level simulations resulted in R^2 values of 0.94 and 0.95 for Scenario 1 and Scenario 2 respectively, which is very similar irrespective of the differences in the closure terms of the water balance terms.

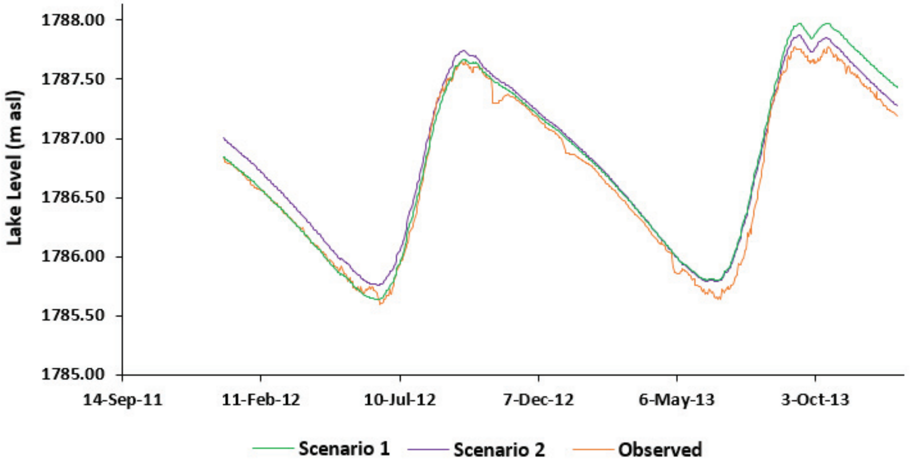

Figure 5.7: Observed and simulated lake levels for the two Scenarios. Scenario 1 simulates the lake level of Lake Tana omitting the floodplain and its effects. Scenario 2 simulates the real field situation (i.e. the lake basin and the lake-floodplain interactions).

5.4 Discussion

5.4.1 The importance of considering floodplains in water balance studies of lakes

The relatively small value of the closure term (82 mm) in the water balance components of the Lake Tana (Table 5.8) and better fit between the simulated and observed lake levels for scenario 2 show that a separate consideration of the floodplain and hillslope catchments whose runoff is affected by the floodplain is appropriate when analyzing the water balance of lakes impacted by a floodplain. The consideration of water abstraction for irrigation has also contributed to the improvement of the closure term. The scenario based water balance studies reveal that $0.42\text{x}10^9$ m^3 of water is abstracted in the floodplain, and will not flow to the lake. The floodplain (representing about 6% of the basin) absorbs and retains mainly storm flows of the crossing rivers. Kebede et al. (2011) indicated that most of the water in the floodplain is lost by evaporation. There are many small ponds (for example, the Shesher and Welala ponds) in the floodplain, where overbank flooded water and runoff from the surrounding hills is stored and subsequently lost as evapotranspiration. The Gumara, Rib and Megech rivers in their downstream reaches (in the floodplain) have low or no flows during the dry season (mostly in April and May). This is mainly attributed to the decline of the groundwater during the dry season, partly due to evaporation and partly due to irrigation. Smallholder irrigations are very common in the floodplain, following the river courses. The studies discussed in Chapter 3 and Dessie et al. (2014a) on the effects of the floodplain on river discharges into Lake Tana show that the runoff contribution from the Rib and Megech floodplains for the lake water balance is negligible. The floodplain abstracts water mainly from overbank flooding of rivers during the beginning of the rainy season (June to July). Studies on the Niger basin by Pedinotti et al. (2012) show similar results and they obtained a strong reduction of the streamflow discharge after crossing an inland floodplain, the so-called "delta", compared to the river discharge before reaching the floodplain.

The source of nearly 60% of the inflow to the lake is the southern part of the lake catchment (Gilgel Abay River), which holds about 38% of the total catchment. This part of the basin receives a large rainfall depth and the influence of the floodplain on the river flows is minimal as compared to the effect of the floodplain on the river flows of the eastern and northern catchments. It follows that any kind of water resource development interventions (for example, construction of dams on the upper catchments for irrigation or other purposes) in the eastern and northern catchments may have more effects on the eco-hydrology of the floodplain than on the hydrology of the lake.

5.4.2 Comparisons to previous water balance studies and potential explanation for some discrepancies

It is interesting to compare the results obtained in this study with those of the previous water balance studies of the lake irrespective of the difference in the years considered for studying the water balance (Table 5.9). We recognize the possible variations with the data considered in this study (years 2012 and 2013 data) and the previous long term water balance studies, and differences in the results of the water balance components of the lake should be evaluated taking this into account.

Table 5.9: Comparison of the Lake Tana water balance terms obtained by different studies

Water balance terms	Results of the different studies on the water balance terms (all in mm)				
	This paper (Scenario 2)	Reintjes et al. (2011)	Wale et al. (2009)	SMEC (2007)	Kebede et al. (2006)
Lake areal rainfall	1331	1347	1220	1260	1451
River inflow	2201	1778	2160	1622	1162
Lake evaporation	-1789	-1563	-1690	-1650	-1478
Lake outflow (discharge)	-1618	-1480	-1520	-1231	-1113
Water abstraction for irrigation (Ungauged catchments)	-42	-	-	-	-
Closure term	82	85	170	1	22

All the river inflows to the lake suggested by the previous studies are smaller than that reported by this study. The river inflow estimates by Wale et al. (2009) and Reintjes et al. (2011) are closer to the results of this study. Disregarding the variations in rainfall during the study periods, the relatively smaller estimates of their studies are possibly due to the regionalization approach they used to estimate the inflows from the ungauged catchments without making any distinction between the hillslopes and the vast floodplain area such that the runoff from the hillslopes might have been underestimated. The river inflow estimates by the other two studies (SMEC, 2007; Kebede et al., 2006) are still much smaller. The ungauged river inflows were determined as the rest term of the water balance by SMEC (2007), resulting in almost no error in the water balance closure term. The estimates were found so small in that negative inflows for some months were observed when a monthly runoff series for the combined ungauged areas was made, and they were not able to explain why. The most likely reason for this is because of the abstraction of water by the floodplain (via runoff transmission losses), as revealed in this study, since the floodplain was not adequately represented in their water balance studies.

Another interesting point is that the lake outflow (discharge) obtained by Kebede et al. (2006) is exceptionally small. While outflow discharges from the lake for this study and for Wale et al. (2009) were obtained from actual measurements (hence relatively closer values), Kebede et al. (2006) used the stage-discharge rating curve while Reintjes et al. (2011) and SMEC (2007) applied both.

The higher value of the lake outflow discharge reported in this study points out that there is more water abstraction in recent times, likely because of diversion of more water to the recently operated hydropower project since the lake outflow is now fully controlled.

The closure term in this study indicates a water balance error as large as 3.5% of the total lake inflow. There are still many sources of uncertainty and errors in the quantification of the water balance. We cannot rule out the possibility of a shortcoming in the conceptual rainfall-runoff model and the inputs mainly related to soil properties in the area. We assumed that lake-groundwater interaction is negligible. The positive closure term (82 mm) in the water balance components challenges this assumption and highlights the need for further research on the possibility of leakage from the lake. However, investigations by SMEC (2007) and Kebede et al. (2011) on the lake and groundwater interaction indicate very little chance of groundwater outflow from the lake. Open water evaporation depth of the lake is estimated by the Penman-combination equation and the rainfall over the lake is calculated using the Thiessen polygon method that relies on rain gauge data observed on the land. Another possible source of error is in the observed data (e.g. rainfall, temperature and river discharge). To prepare the rating curve, flow velocity was measured using the float method for flood discharges with uncertainties in the float method of flow velocity measurement. River discharge observations are usually obtained by means of the rating curve by converting measurements of river stage into river discharge by using this rating curve function. Hence, an additional error might be induced by the imperfection of the rating curve. Pelletier (1987) pointed out that the overall uncertainty in a single determination of river discharge, at the 95% confidence level, can vary in the range 8%-20%.

Despite the aforementioned uncertainties that also challenged all the previous water balance studies of the lake, this research has shed some light on the impact of the floodplain on the lake water balance and it could explain why the ungauged runoff estimations by the previous studies were so small even though the ungauged catchments constituted nearly 60% of the total lake catchment. The extensive lacustrine floodplain with more than 900 km^2 size is the hydrological connector between the lake and the upper catchments. Floodplains are considered as specific ecosystems (Junk, 1996) and water balance studies need to take note of this to get a better picture of the lake basin system.

5.5 Conclusions

The Lake Tana water balance analysis presented in this chapter describes the different water balance components of the lake and provides a meaningful assessment of the components. It demonstrates the importance and the influence of the extensive floodplain on the water balance of the lake.

In this study, a complete hydro-meteorological data set including the data from recently established meteorological stations was used and lake evaporation computations benefited from the air temperature data of stations near the lake. Uncertainties of runoff from the ungauged catchments were reduced by increasing the gauged catchments coverage from 42% (the case for the previous studies) to almost 60% (with high temporal resolution) and a different, more refined approach to estimate the runoff from the remaining ungauged catchments is used. A distinction was made between the floodplains (including hillslope catchments that are affected by the floodplain) and the hillslope catchments to estimate their runoff in that a simple conceptual rainfall-runoff model is applied for the hillslope catchments and a runoff coefficient approach for the floodplain and its affected catchments. The results show that 18% of inflow of Lake Tana is from ungauged systems while they constitute nearly 40% of the lake basin.

The impact of the floodplain on the water balance of the lake was made by comparing the results of the water balance analysis with and without considering the floodplain. We note that nearly half a billion m^3 of river inflows to the lake are abstracted annually via runoff transmission losses in the floodplain.

The water balance analysis of the lake resulted in a mean lake rainfall depth of 1330 mm, open water evaporation depth of 1789 mm, river inflow depth of 2201 mm and outflow discharge depth from the lake of 1618 mm. Simulated lake levels compare well with the observed lake levels ($R^2 = 0.95$) and the water balance can be closed with a closure error of 82 mm/year that accounts for 3.5% of the total lake inflow, which is small compared to the closure terms of Wale et al. (2009) and Reintjes et al. (2011).

There are still several sources of uncertainty and errors in the water balance. This study, unlike the previous water balance studies, is more comprehensive by providing a separate analysis of the floodplain and the catchments influenced by the floodplain. Uncertainties of the runoff estimations from ungauged catchments is also reduced by decreasing the size of ungauged catchments from about 60% to 40%. This is an improvement on the water balance of Lake Tana and the results may contribute to a better management of the lake water and fauna and flora resources of the floodplain. Moreover, the sensitivity analysis revealed that evaporation is more sensitive to temperature. Hence, from this study we can also infer that climate and land use changes (conversion of the floodplain into agricultural lands and settlements) will affect the water balance of the lake. To further progress in the hydrological and hydrodynamic understanding of the lake and the basin as a whole, rainfall upon and open water evaporation from the lake surface needs improved study. Our water balance model ignored groundwater infiltration due to the absence of detailed data on these processes in the lake and its floodplain. This might partly explain the observed small positive bias in the water balance simulations (i.e. slightly overestimating the inflows since the closure term is positive). We, therefore, highlight the importance of starting a continuous groundwater measurement campaign within the floodplains and conducting a detailed modelling exercise on floodplain-groundwater interactions.

CHAPTER 6

6. Scenario-based decision support for an integrated management of water resources[4]

Abstract

In this study, analyses of future scenarios of water demand and supply as well as an assessment of trade-offs for water allocation across the different water use sectors are made. Different periods of regulation of Lake Tana and subsequent impacts on the lake level hydrological regime are investigated. A decision support system is developed and available water supply for normal and low flow hydrological conditions are determined based on recorded flow data and a simple rainfall-runoff model. Different scenarios have been triggered and simulations are conducted to understand the implications of planned water resource developments in the area. We obtained that the inflows to Lake Tana under an average hydrological condition are about 5.7 $x10^9$ m^3 and are estimated to reduce by about 27% when all planned water resources development projects are implemented in the catchment. These projects aim at the generation of 460 MW hydroelectric power and about a billion m^3 per annum supply of water to the large-scale irrigation schemes. During low flow conditions, supply will run short of demands and the lake water level can drop by 0.3 m from the natural outlet level (1785 m a.s.l). An upstream-downstream cooperation, transparency and participation in the decision making and establishment of an adequate data acquisition system are critically important elements in the management of water resources in the basin.

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6.1 Introduction

The first guiding principle of Integrated Water Resources Management (IWRM) states that freshwater is a finite and vulnerable resource, essential to sustain life, development and the environment (ICWE, 1992). The potentially available fresh water for use represents less than 1% of all water in the world, while the rest is saline (97%) or is locked up as glaciers and icecaps (Postel et al, 1996). Population growth and the rising demand in various sectors of consumption of fresh water are becoming a severe strain on these limited fresh water resources of the world. In view of this, researchers have assessed the future status of water supply and demand under various climatic and hydrological conditions (e.g. Varis et al., 2004; Jeong et al., 2005; Pallottino et al., 2005; Ali et al., 2014), water resource development plans (e.g. Koch et al., 2005; Loukas et al., 2007) and water demand management practices (e.g. Lévite et al., 2003; Chen et al., 2005). By 2050, almost 40% of the world population (3.9 billion people) will live in areas of high water stress (OECD, 2012). Hence, the need to improve water management to maximize benefits and minimize negative environmental and social (including health) impacts has attained increased recognition worldwide. Due to the complex spatial and temporal features of water and related ecosystems, articulated and complex policies and fragmented knowledge about socio-ecosystems, water managers and decision makers need alternative scenarios and reliable information on the impacts of the various water resource development projects during their planning, implementation, operation and management. Decision support systems (DSS) have recently been used to support basin-scale mid- and long-term planning and management (e.g. Tidwell et al., 2004; Fassio et al., 2005; Janssen et al., 2005; Georgakakos, 2007; McCartney, 2007; Giupponi and Sgobbi, 2013). A DSS provides an effective platform for management and strategic planning and an understanding of the current system, future impacts of upcoming projects, climate change as well as land-use change. However, the specific decision support tools and methods to be used depend on the case.

Effective water resources development is crucial for sustainable economic growth and poverty reduction in Ethiopia (World Bank, 2006; Grey and Sadoff, 2006) and the country has started to pursue different water resources projects in its various river basins in general, and in the Blue Nile in particular. The Lake Tana basin is a good instance for this, where the development of various irrigation schemes to irrigate more than 115,000 ha of land and hydropower generation (currently 460 MW power plant is operational) is taking place. It is worth evaluating the impacts of these developments on the Lake Tana levels and on the environment through an appropriate DSS. Such an evaluation is crucial because this rather shallow lake (maximum depth is ca. 14 m) and the wetlands in its vicinity are sources of domestic water supply, fisheries, water for livestock, biodiversity and water transport. A review of studies by Tesfahun and Demissie (2004) indicate that the management of resources in and around the lake have been unsustainable and are hardly controlled. McCartney et al. (2009) reported that dry season outflows from the lake have been insufficient to maintain even basic ecological functioning of the Abay River reach (natural outlet of the lake). Simulations of the implication of large irrigation and hydropower development projects in the basin revealed that the mean annual water level of the lake will be lowered by 0.44 m when the planned projects are fully realized (Alemayehu et al., 2010). A number of questions still remain to be properly addressed for a better understanding of the impacts and decision making in the basin. In the Lake Tana basin, in addition to the planned large-scale irrigation projects, small-scale irrigation projects (not accounted for by the study of Alemayehu et al., 2010) are quite common with possible expansion in the future and demanding a substantial share of water, hence there is a need to consider these in the study. Moreover, it would be much more practical and helpful for the managers and decision makers to formulate and show scenario-based impacts of the various development options under different hydrological regimes (for an average water year and for a drought or low flow period based on the inflow data series) on the lake system. Water level is a key hydrological variable and a useful indicator in lake management practices (O'Sullivan and Reynolds, 2004). It enables to understand the variability of the hydrological conditions of a lake, and this variability in turn determines factors influencing geomorphology, habitat quality, water quality, as well as biodiversity of the lake (Smakhtin et al., 2004; Mitsch and Gosselink, 2007). Therefore, any water resources development interventions on Lake Tana and its basin need to operate as closely as possible to its natural regime to maintain particular ecological characteristics which are able to provide important goods and services. The lake experienced four periods of different flow regulation since monitoring of the lake level started. It is vital to investigate whether the artificially regulated lake levels (in all periods of regulation) are appreciably affected to a level that disturbs the ecology of the lake system.

As discussed in the previous chapters, a comprehensive and reliable hydrological data collection at high temporal resolution has been established recently (since 2011) in the Lake Tana basin and a comprehensive water balance study of the lake showing the impacts of the floodplain has also been made (Chapter 5 and Dessie et al., 2015). Hence, this study builds on such reliable data and recent studies to further understand future water resource development impacts on the lake.

This chapter investigates the likely impacts of different development options on the lake level and the associated ecological and social consequences under varying hydrological regimes on a monthly basis by simulating three scenarios. The first scenario is a baseline scenario, which simulates the lake level condition based on currently available operational water resource projects (until 2013) in the basin and for the hydrological variables observed in the year 2013. The second scenario corresponds to the lake level changes when the planned large-scale irrigation projects, small-holder irrigation activities and hydropower projects are fully pursued and recommended environmental conditions are maintained, considering an average (normal) hydrological condition based on 32 years of historical flow data in the basin. The third scenario is similar to the second one except that the average hydrological condition is now replaced by a drought hydrological condition (low flow case with ca. 20% reduction of the river discharges from the average hydrological condition). The study quantifies changes in river flow and the amount of water shortage for each case when there is deficiency, and suggests the possible allocation of water based on proposed priorities. The study also aims to compare and to assess whether the different periods of lake level regulations experienced so far have appreciably affected the natural hydrological regime of the lake. More importantly, a decision support is made available in this study by developing a user-friendly decision support framework for a better decision in the current operation of the lake and for a better planning and management of the upcoming projects in the basin.

6.2 The decision support system (DSS) and its elements

6.2.1 Conceptualization of the DSS

Various concepts and definitions exist for a DSS in the literature, and its ambiguity has been discussed by several authors (e.g. Keen, 1981). Watkins (1995) defines a DSS as an integrated, interactive computer system, consisting of analytical tools and information management capabilities, designed to aid decision makers in solving relatively large, unstructured problems. It indicates that a DSS is not a single application, but a collection of suitable components including a geographic information system (GIS), a set of simulation models, as well as functionalities for data and time series analysis and multi-objective evaluation of results.

Decision support systems have gained wide applications in water resources for flood control and risk management (e.g. Cunge et al., 1991; Brimicombe, 1992; Simonovic, 1993), for lake and reservoir management (e.g. Henderson-Sellers, 1991; Georgakakos, 1991; Condappa et al., 2009), for groundwater water management (Frysinger et al., 1993; Hadded et al., 2013) and for many other water resource issues.

Using the aforementioned concept of a DSS and based on Georgakakos (2007), we developed and applied a DSS (Fig. 6.1) for the Lake Tana basin (generating three scenarios) to assess the implications of different water resources development plans and to show better management options of the resource in the basin. The DSS consists of different components (Fig. 6.1): data acquisition system, user-data-model interface, database, data analysis and evaluation and finally the decision. The data acquisition system involves every means by which generic data are collected and made available to the DSS. The database contains readily available data (topographical data, hydro-meteorological data, land use, soil, catchment characteristics, water demand, reservoir characteristics etc.) for analysis and evaluation. The user-data-model interface enables transfer of data to the data base (depository of all data acquired through different mechanisms) and creates an environment for easy and meaningful access to data, data analysis tools, and application programs or models. The data analysis tools and models provide user-friendly means to analyze, generate, visualize and evaluate various data sets to produce information and knowledge vital for the decision makers.

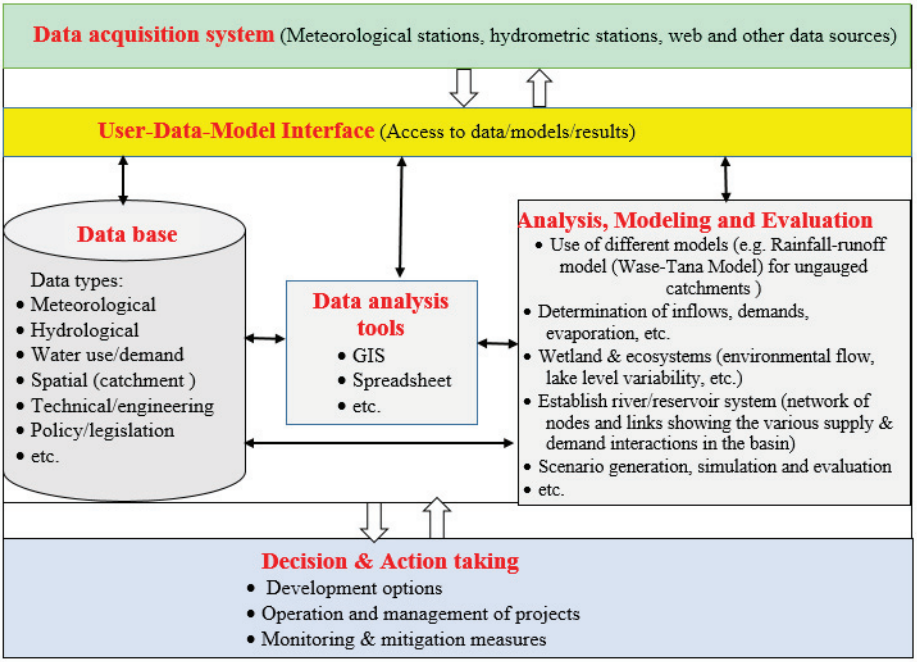

Figure 6.1: The decision support system and its components (modified from Georgakakos, 2007)

6.2.2 Data acquisition system in Lake Tana basin

So far, the data acquisition and information system was not well organized and there was no well-established database system in the basin to feed decision support systems to address ongoing concerns related to the water problems and climatic conditions. The various data of interest are normally collected from different organizations and sources in the country.

There are 40 meteorological stations (owned by the National Meteorology Agency of Ethiopia) within and near the Lake Tana basin (Figs. 2.11 and 6.2), most of which only record daily rainfall depth and air temperature.

The Ministry of Water, Irrigation & Energy collects hydrometric data officially in the basin with current coverage of not more than 42% of the basin area. Moreover, recently additional hydrometric stations have been installed in the basin for specific project oriented purposes and this has increased the gauged catchment area coverage to 60%

(Figs. 2.11 and 6.2). It is worth mentioning the hydrometric stations implemented in the basin since 2011 by the Wase-Tana Project (http://geoweb.ugent.be/physical-geography/research/wase-tana) for this study. The discharge data obtained from these hydrometric stations are with high time resolution (discharge data every 20 minutes or lesser are available). Moreover, the location of the stations were selected to represent the major rivers in the basin at their hillslope and downstream reaches for a better understanding of the hydrological system in the hills and downstream reaches.

Lake Tana levels are recoded at three stations (i.e. Bahir Dar, Gorgora and Kunzila stations, Fig. 2.11). The data recorded at Bahir Dar have both long record periods (since 1959) and good quality so that these data are mostly used for the analysis by researchers and analysts. Bathymetry surveys of the lake have been conducted at different times. The oldest one was published by Morandini (1940), followed by Studio Pietrangelli (1990). A bathymetric survey by the Institute for Geo-information Science and Earth Observation (ITC) (Kaba, 2007) was also made. A detailed and broader study of the bathymetry of Lake Tana was conducted by Omega Development Service Plc in 2012, promoted by the Ethiopian Ministry of Water, Irrigation and Energy.

6.2.3 Planned and operational water resource developments and water demands

The Lake Tana basin hosts more than 3 million inhabitants (CSA, 2003) and the majority of the population lives in rural areas, whose livelihoods are mainly dependent on rain-fed agriculture. As a result of its significant water resources potential, the basin has become the focus of the government for water resource development and a number of irrigation schemes on the major tributaries to the lake are under implementation and planned for the future (Fig. 6.2). The introduction of the irrigation schemes will provide the farmers more security about their basic food supply and enable them to diversify their crops based on local market demand and export opportunities. The large-scale irrigation projects are to be realized through the construction of dams on the major tributaries and pumping of the Lake Tana water (Fig. 6.2 and Table 6.1). From the large-scale irrigation projects planned in the basin, only the Koga irrigation project is operational to irrigate 7000 ha. Based on the Abbay Basin Master Plan studies, BCEOM (1998b) has identified a net irrigation area of 121,260 ha in the Lake Tana basin (10% of the basin area, excluding the lake), while recent studies by Wale et al. (2013) calculated the potential for irrigation in the basin at 11% (or about 132,000 ha). If we consider an average figure i.e. about 127,000 ha, we conclude that nearly 89% of the potential for irrigation is to be realized through large-scale irrigation projects (Table 6.1), while the remaining ca. 15,500 ha of land is through small-scale irrigation activities.

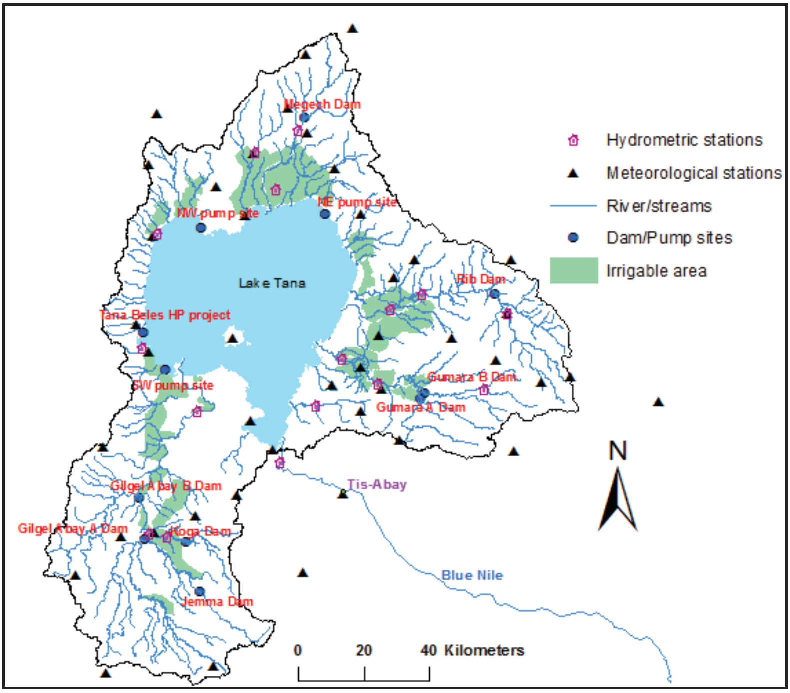

Figure 6.2: Lake Tana basin with location of planned projects, irrigable area and hydrometeorological networks

Some 32 km down stream of Lake Tana (near the Blue Nile Fall), there are Tis Abay I and II hydroelectric power plants with generating capacity, respectively, of 11.4 MW and 73 MW. Tana Beles hydropower station, with generating capacity of 460 MW by transferring a mean annual discharge of 84 m^3/s of water (based on 2012 and 2013 data from the Tana Beles hydropower project) from Lake Tana via a 12 km long tunnel, has been operational since May, 2010. After the Tana Beles hydropower project has been operational, the Tis Abay I and II hydroelectric power plants were mothballed as the outflow from the lake was diverted to Tana Beles hydropower station.

There are different water use sectors in the Lake Tana basin (irrigation, hydropower, domestic water supply, environmental flow, industrial water use, navigation, tourism mainly due to Blue Nile Falls). In this study, the monthly irrigation water demands for the implemented and planned large-scale irrigation schemes were obtained from the project studies (WWDSE, ITC 2008; WWDSE, TAHAL 2008a; 2008b) and from the Abbay River basin Integrated Development Master Plan. The annual irrigation demands for the various large-scale projects in the basin varied from 816-1129 mm (Table 6.1). To estimate the water demands for the small irrigation practices in the basin, we used an average value of 973 mm and a similar cropping pattern and monthly water demand distribution to the operational Koga irrigation project. We assumed that 5% of the irrigation water supplied to irrigation schemes will eventually be returned to the rivers as drainage water. Evaporation from the reservoirs (dams) is also depicted in Table 6.1 (for details, see Section 6.2.6).

A considerable magnitude of water used for domestic, municipal and industrial consumption is extracted from the groundwater and the impact of these sectors of water use on the lake, both now and in the future, is considered insignificant (SMEC, 2008) compared to the irrigation projects. Hence, the water abstraction by the cities in the basin is not considered in this study. Exception to this is the city of Gondar, as its water demand in the near future will be abstracted from the Megech reservoir (Fig. 6.2). Domestic demand for Gondar town was taken as 31.5×10^6 m^3 annually (WWDSE, TAHAL 2008b). The water demand by the Tana Beles hydropower generation for the years 2012 and 2013 was obtained directly from the Tana Beles hydropower plant and a similar water demand pattern is expected for the plant in the future.

Table 6.1: Planned and operational irrigation developments in the Lake Tana basin (source: BCEOM, 1998b; MacDonald 2004; WWDSE, ICT 2008; WWDSE, TAHAL 2008a; 2008b). Mm^3 stands for million m^3. NA is not applicable. A and B for Gumara and Gilgel Abay are used to differentiate the dams at upstream and downstream of the same river.

Irrigation Project (Dam or Pump)	Irrigable area (ha)	Estimated annual irrigation water demand (Mm^3)	Estimated annual reservoir evaporation (mm/year)	Estimated Dam storage capacity (Mm3)	State of development in 2014*
Gumara A	14000	138.3	1842	134	Feasibility study completed
Gumara B	13976	138.1	1842	136	Identification
Rib	19925	196.9	1772	216	under construction
Megech	7300	59.6	1980	162.7	under construction
Gilgel Abay A	12069	136.3	1644	331	Identification
Gilgel Abay B	12852	145.1	1644	136	feasibility study
Jemma	7786	87.9	1644	99	Identification
Koga	7000	65.4	1644	82.6	completed and operational
NE lake pumping	5745	41.1	NA	NA	Identification
SW lake pumping	5132	36.7	NA	NA	Identification
NW lake pumping	6720	48.1	NA	NA	Identification
Total	**112505**	**1093.4**		**1297.3**	

*identified in the field and based on project documents from relevant offices

McCartney et al. (2009) made a detailed evaluation of the environmental flow requirements needed to maintain the basic ecological functioning of the reach leading from the natural outlet from the lake to the Tissat Falls (Blue Nile Falls) (Table 6.2) and these study results are taken as the minimum water release needed any time for environmental reasons from Lake Tana. Low flow contributions from tributary streams within the reach to the Blue Nile Falls is assumed insignificant, and allowance for maintaining the aesthetic quality of the falls from the lake is not considered in this study. For other dam projects in the basin, the minimum in-stream flows based on recorded or modelled flows for each river affected by the dams is kept as the minimum environmental flow requirement downstream of each reservoir when there is shortage of water.

Table 6.2: Water balance terms of Lake Tana and environmental flow requirements at Blue Nile Falls

Month	Lake Tana monthly water balance terms for 2013 (Chapter 5 and Dessie et al., 2015)					Estimated environmental flow requirements at Blue Nile Falls (McCartney et al., 2009) in Mm^3
	Inflow from river discharges (Mm^3)	Rainfall on the lake (Mm^3)	Evaporation from the lake (Mm^3)	Outflow from the lake to the Blue Nile Falls (Mm^3)	Outflow from the lake to Tana-Beles hydropower (Mm^3)	
Jan.	115.9	0.0	465.7	54.0	277.4	68
Feb.	94.9	0.7	509.9	25.3	234.7	56
Mar	96.8	1.9	625.0	22.6	289.0	42
Apr	86.7	1.5	645.2	21.0	282.9	28
May	129.3	77.5	606.8	42.5	244.9	23
Jun	262.7	477.7	377.6	23.6	158.2	21
Jul	1750.5	1319.9	312.9	35.5	248.8	39
Aug	2083.4	1482.2	261.2	157.4	269.4	83
Sep	1140.4	618.0	356.6	1041.9	217.0	192
Oct	567.5	446.6	439.6	405.6	160.6	117
Nov	159.7	9.0	425.7	264.4	191.0	109
Dec	108.9	13.0	399.4	141.4	230.2	86

6.2.4 Water availability

Critical to any water resources planning and development is reliable information on the quality and quantity of available water supply in the basin. A detailed water balance study of Lake Tana has been made as shown in Chapter 5 and Dessie et al. (2015), and hence the monthly inflows, evaporation, and rainfall for the lake (Table 6.2) in 2013 (baseline scenario) are used in this chapter to analyze the impacts of the different water resources interventions on the lake. River discharges upstream and downstream of proposed dams for the ungauged catchments were quantified using measured data for the gauged catchments and the hydrological model developed in Chapter 4 and Dessie et al. (2014b).

a) The hydrological model

The hydrological model, developed in Chapter 4 and Dessie et al. (2014b), is used to compute discharges of ungauged catchments (inflows to the reservoirs and downstream of the reservoirs). However, in some cases inflows into the reservoirs and downstream of the reservoirs from the ungauged catchments were also computed using area-weighted estimates from the nearest available flow gauging station. The results were compared with the hydrological model, producing almost similar results. Both methods were applied for Megech, Jemma and Gilgel Abay A Dam reservoirs (Fig. 6.2). The hydrological model was applied to obtain inflows into the remaining Koga, Gilgel Abay B, Rib, Gumara A and B dam reservoirs (Fig. 6.2).

b) Data input to the model

The inputs for the hydrological model were topographical data (catchment area, slope and slope length), soil data (depth, porosity, field capacity, and hydraulic conductivities of soils) and weather data (precipitation and potential evapotranspiration). From the potential evaporation, the model calculates the actual evaporation.

The global digital elevation model (GDEM) was used to extract the topographical data. Soil depth and soil type data were obtained from the Abay River basin integrated master plan study (BCEOM, 1998a). The other soil data were estimated based on the method described in Chapter 4 and Dessie et al. (2014b). Meteorological data such as minimum and maximum air temperature, humidity, wind speed and duration of sunshine hours were used to calculate the potential evapotranspiration. The weather data were obtained from the Ethiopian National Meteorological Agency (NMA) stations located within and around the catchments (Figs. 2.11 and 6.2).

c) Model calibration and validation

We calibrated and validated the model with observed river flows from a gauged catchment that is considered hydrologically similar to the ungauged catchment (mostly in the same mother catchment but upstream or downstream of the outlet of the gauged catchment). Therefore, we used the calibrated parameters of the Picolo station observed discharge data to estimate inflows for the ungauged part of the catchment at Gilgel Abay B dam site, Koga observed discharge data near Wotet Abay town (also Picolo town) for Koga catchment at Koga dam site, Gumara at Wanzaye station observed discharge data for catchments at Gumara A and B dam sites and Rib near dam site station observed runoff data for the catchment at Rib dam site (Fig. 6.2). The model calibration and validation were performed at a daily time step, and using different length of the hydrological data set (minimum two years). The calibrated parameters of the model are given on Table 6.3.

Table 6.3: Model parameters and calibrated values found after 3500 iterations in the Particle Swarm Optimisation (PSO) calibration

Parameter	Explanation	units	Calibrated values			
			Gilgel Abay at Picolo	Koga	Gumara at Wanzaye	Rib near dam site
β	parameter to account variability of permeability of soil with soil water storage	_	2.31	2.09	2.45	2.10
k1	relates discharge and storage for the ground water	_	1.01	0.63	0.97	0.59
$K_{s,u}$	Saturated hydraulic conductivity in the upper soil layer	m/s	0.05	0.016	0.016	0.01
γ	parameter to account variability of deep percolation with soil water storage	_	0.9	1.32	1.41	1.13
λ	fraction of catchment that is impermeable	_	0.173	0.059	0.1489	0.082
$\alpha 1$	interflow partitioning coefficient for the steep slope surface	_	0.575	0.479	0.653	0.652
$\alpha 2$	Interflow partitioning coefficient for the medium slope surface	_	0.152	0.096	0.065	0.063

6.2.5 The lake system before and after interventions

Time series of daily water level data for Lake Tana from 1959 to 2013 were obtained from the Ministry of Water, Irrigation & Energy of Ethiopia. The lake experienced four periods of different flow regulations since monitoring of the lake water level started in

1959. There was no regulation or control of outflow from the lake for the period 1959-1996 (only natural factors governed its outflow, hence lake water level variability followed the natural regime of the lake). From 1996-2000, the lake was regulated using two gates (Two-gated Chara Chara weir became operational in May 1996 to regulate the flow to the Tis-Abay-I power station). Following the implementation of another hydropower station (Tis Abay-II power station), five new additional gates were constructed and were operational in January, 2001. This third alteration in the lake outflow lasted only for almost 10 years (2001-2010), until a 460 MW Tana Beles hydropower station diverting the lake water through a tunnel to the station (to the Beles River after power generation) was established in May, 2010. The Chara Chara weir regulates water storage in Lake Tana over a 3 m range of water levels (i.e.1784 m. a.s.l. to 1787 m. a.s.l) and the active storage of the lake between these levels is about 9100 $x10^6$ m^3 (Alemayehu et al., 2010).

The significance of the lake level variability (Fig. 6.3) with respect to its natural variability (1959-1996) for the different periods of regulation has been assessed using parametric statistical tests (two sample t-test). The two-sample t-test (Snedecor and Cochran, 1989) is used to determine if two population means are equal (i.e. if natural lake level variability is similar to the variability for the other periods of regulation). The study is made by dividing the water level data into two categories, as low water level condition (February- July) and as high water level condition (August-January) for each of the four periods of regulation. The classification in low and high water level conditions is important because each of these conditions plays different roles in the ecological functioning of the lake. The low and high water level series data were tested for normality (Fig. 6.4) as parametric statistical procedures rely on normal distribution of the samples. The data series in all the four periods of different flow regulations of the lake follow a normal distribution as can be seen in Fig. 4.6 for the two periods.

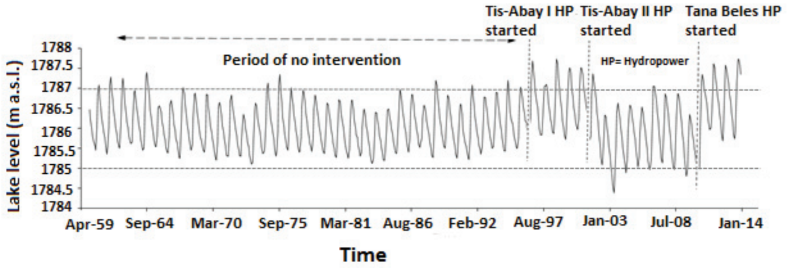

Figure 6.3: Water level fluctuations of Lake Tana in relation to interventions or regulations

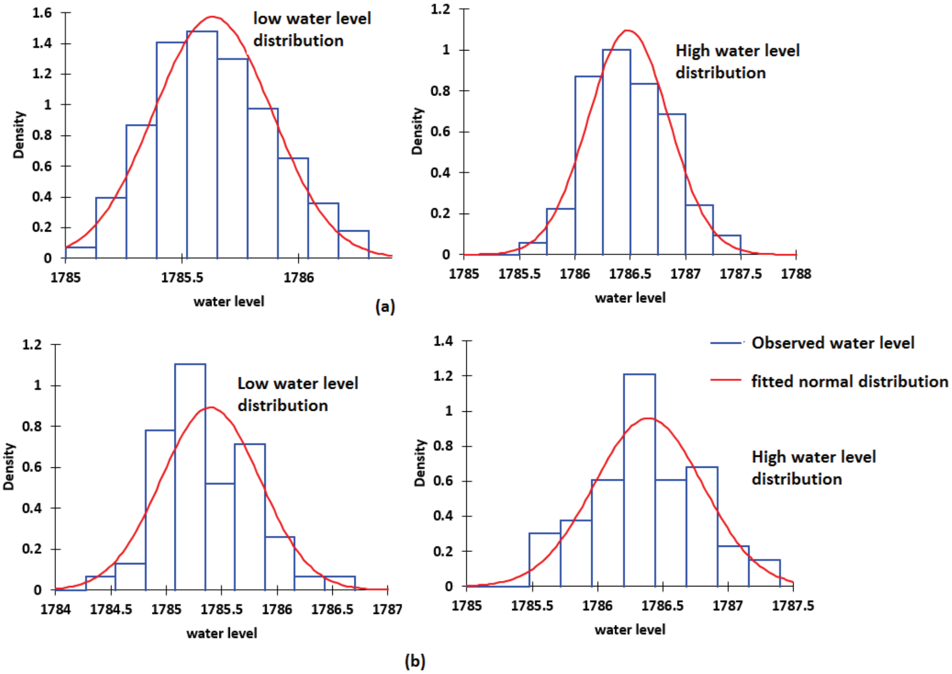

Figure 6.4: Lake Tana water level (m a.s.l.) distributions under low and high water level conditions (a) for the period before regulation of the lake (1959-1996) and (b) for one of the regulated periods (2001-2010).

6.2.6 Simulations and decision support scenarios

a) The river/reservoir system

Simulation techniques were employed to analyze the impact of the various anthropogenic activities (mainly the upcoming planned water resources development projects) on the natural system to influence water resources and their allocation in the Lake Tana basin. For this purpose, a spatial configuration of the river/reservoir system (Fig. 6.5) of the basin is constructed to represent the system in terms of its various supply sources (e.g. rivers, creeks, inter-basin transfer and reservoirs); water demands and withdrawals (hydropower, irrigation, domestic supply, etc.) and ecosystem requirements. Components of the system are depicted as a network of nodes, both storage (i.e., reservoirs and groundwater basins) and non-storage (i.e., river confluences, diversion points, and demand locations), and links (i.e. canals, pipelines, and natural river reaches) connecting the nodes.

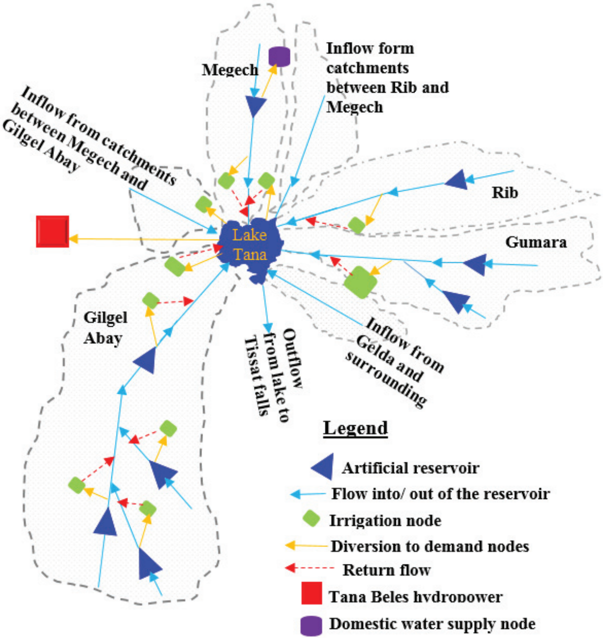

Figure 6.5: A spatial configuration of the river/reservoir system in the Lake Tana basin showing the supply and demands for the various planned and operational projects in the basin

The movement of water through a system of reservoirs and river reaches is tracked based on volume-balance accounting procedures.

$$S(t) = S(t-1) + P(t) + Q_{in}(\mathrm{t}) - E(t) - Q_{out}(t) \qquad (6.1)$$

where $S(t)$ is the storage at time t, $S(t-1)$ is the storage in the preceding time $t-1$, $P(t)$ is the rainfall on the reservoir at time t, $Q_{in}(\mathrm{t})$ is the inflow or runoff into the reservoir at time t, $E(t)$ is the evaporation from the reservoir at time t, and $Q_{out}(t)$ is the outflow from the reservoir (this includes spills from the reservoir when the reservoir is full, environmental flow requirements and demands for the various uses). All units are in 10^6 m^3.

The daily evaporation depth from the reservoirs was estimated by the Penman combination method (Maidment, 1993), which is widely applied as a standard method in water resources engineering. This technique combines the energy balance and the water vapor transfer methods to compute the evaporation of open water surfaces using daily sunshine hours, air temperature, air humidity and wind speed data. For this purpose, meteorological data on daily maximum and minimum air temperature, wind speed, relative air humidity and sunshine hours were collected from the relevant stations (Figs. 2.11 and 6.2).

A spreadsheet model was developed to compute and simulate reservoir storage contents and spills from the reservoirs for the input sequences of stream inflows and net reservoir surface evaporation rates (rainfall plus evaporation) on monthly basis for the specified water demands and available water supplies. Elevation-area-capacity data for the various reservoirs in the basin were obtained from the project feasibility studies.

b) Scenarios and hydrological classification

Three scenarios were analyzed in this study. For the description of the scenarios, we refer to Section 6.1 (Introduction). The three scenarios enable to understand the impacts of the water resource developments on the lake under normal and hydrological drought conditions in the basin for a better water allocation and reservoirs operating strategies.

The average and low flow hydrological conditions were determined from 32 years (1976-2007) historical data of the mean annual discharge of the four hydrometric stations on the

Gilgel Abay, Gumara, Rib and Megech Rivers (representing more than 93% of the inflow to Lake Tana). Flow duration curves can be used as a general indicator of hydrological conditions (i.e. wet versus dry). Flow duration curves are cumulative frequency distributions that show the percentage of time that a specified discharge is equaled or exceeded during a period of interest (daily, monthly, annual, or entire period of record). Q_{90}, i.e. the flow that is exceeded 90% of the time, is commonly used as a low flow index (Smakhtin et al., 1995).

A flow duration curve (Fig. 6.6b) was prepared to show the complete range of the annual total discharge (from low flows to flood events) at the hydrometric stations on the four main rivers. Q_{90} was found to be ca. 82.5 m^3/s, and in this chapter any year with annual discharge less than or equal to this value (for the four monitoring stations) corresponds to a low flow year (dry year). Likewise, Q_{10} is used to represent the high flow index and the value is ca. 130 m^3/s (i.e. any year with annual discharges $\geq$ 130 m^3/s is a high flow year or wet year). Any year with discharges larger than 82.5 m^3/s but less than 130 m^3/s is considered as a normal flow year (average hydrological condition), having an average value of 106 m^3/s (same as mean annual flow for the 32 years data). Using these indices, the 2013 year inflows from the basin into the lake and other reservoirs were adjusted to low inflows and average inflow conditions for simulating scenario 2 and 3. Lake level, river flows and water supply reliability are evaluated for three scenarios in the river/reservoir system of the basin (Fig. 6.5).

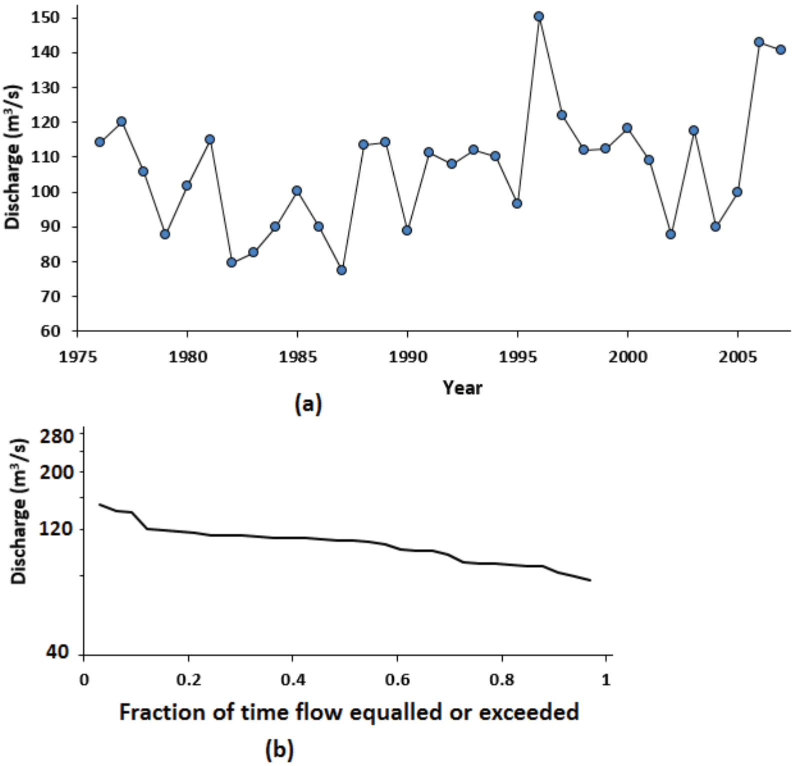

Figure 6.6: Mean annual discharge (a) and flow duration curve (b) of the main rivers flowing towards Lake Tana at Gilgel Abay near Picolo, Gumara near Bahir Dar, Rib near Addis Zemen, and Megech near Azezo hydrometric stations

6.3 Results

6.3.1 Estimated inflows, the hydrological model performance and uncertainty

To estimate the inflows to the artificial reservoirs in the basin under consideration, four catchments with observed discharges were modelled (Table 6.4). The estimated inflows to the reservoirs using the model application are also depicted in Table 6.5. The Megech and Koga dam capacities (Table 6.1) are close to the total annual runoff yield of their catchments (Table 6.5) and spills as excess flow are expected to be less frequent or nil. From Table 6.4 of the model performance results, we see that the Nash-Sutcliffe Efficiency (NSE) varies from 0.57 to 0.86 for the calibration period and from 0.5 to 0.78

for the validation period in the selected catchments. The simulated and observed runoff discharges from the two catchments (Koga and Rib near dam) for the calibration period are depicted in Fig. 6.7. Details of the modelling, uncertainty and performance for the other two catchments (Gilgel Abay at Picolo and Gumara at Wanzaye) are discussed in Chapter 4 and Dessie et al. (2014b). Model performance for the Koga catchment was poor. As explained in Chapter 5, it is also noted here that the uncertainty of the hydrological model is relatively high in small catchments besides uncertainties associated with the input data to the model. However, for such planning and decision support studies, results are considered as satisfactory. This is because the model performance results are assessed on a daily flow basis, while the planning and decision support studies are based on the monthly and annual flow results. The larger the modelling scale (both in time and space), the less uncertainty is involved (Loosvelt, 2013): errors at the point scale compensate each other when averaged over time such that the resulting error at the monthly or annual basis is significantly less.

Table 6.4: Model performance results of the modelled catchments

Model performance indicators		Gilgel Abay at Picolo	Koga	Gumara at Wanzaye	Rib near dam site
Calibration	R^2	0.85	0.56	0.86	0.72
	RMSE (m^3/s)	38.1	5.4	20.0	4.9
	NSE	0.84	0.57	0.86	0.70
Validation	R^2	0.8	0.55	0.8	0.72
	RMSE (m^3/s)	35.7	5.0	25.9	5.3
	NSE	0.7	0.5	0.78	0.72

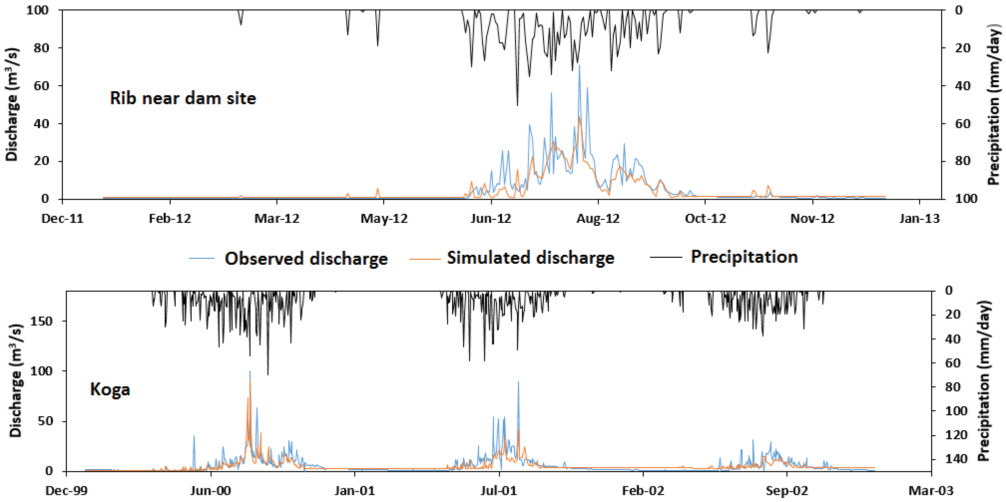

Figure 6.7: Comparison of simulated and observed discharges of Rib near dam site and Koga for the calibration period

Table 6.5: Estimated inflows to the reservoirs of planned and operational dams for the baseline year

Estimated inflows (Mm^3/month) to the reservoirs of planned and operational dams for the baseline year (2013)								
Month	Rib	Gumara A	Gumara B	Megech	Gilgel Abay A	Gilgel Abay B	Koga	Jemma
Jan.	6.47	3.51	5.13	1.20	31.28	22.66	5.67	10.84
Feb.	5.14	3.74	3.47	0.97	12.77	18.47	5.10	4.42
Mar	5.28	3.36	3.20	0.93	11.02	18.53	5.58	3.82
Apr	5.03	3.78	3.29	0.62	9.04	17.26	5.30	3.13
May	5.94	8.86	13.35	1.09	55.00	23.39	6.80	19.05
Jun	11.00	13.62	33.61	4.25	150.34	121.66	7.58	42.28
Jul	96.02	122.16	133.37	42.63	411.53	537.96	25.08	142.54
Aug	118.70	174.38	111.44	79.29	365.14	531.62	24.01	126.47
Sep	27.20	58.91	57.99	32.31	246.76	363.21	19.41	85.47
Oct	10.16	33.71	55.11	3.14	147.57	186.16	10.72	51.11
Nov	6.72	7.10	8.97	2.17	65.69	67.37	7.63	22.75
Dec	6.92	4.89	5.70	0.90	36.29	26.22	7.67	12.57
Total	**304.59**	**438.02**	**434.64**	**169.50**	**1542.44**	**1934.52**	**130.55**	**524.45**

6.3.2 The lake hydrological regime before and after regulations

The parametric statistical studies (Table 6.6) and the lake water level duration curve (Fig. 6.8) clearly indicate how the Lake Tana water levels are affected due to regulation in comparison to the natural water level regime of the lake. The p-values of the two-tailed t-test (Table 6.6), obtained by testing the water levels of the 1960-April 1996 (period of no regulation and the lake system is operating under its natural regime) with each of the three lake level regulation periods for both the low and high water levels, show that the change in the hydrological regime of the lake with respect to its natural water levels was statistically significant in all of the regulation periods except for the period from Jan. 2001- April 2010 for the high water levels.

Table 6.6: Lake Tana levels; the significance of the difference between the no regulation period and the regulation periods for both low and high water levels is shown by the result of two-tailed t-test for independent samples.

Variable	Regulation periods	Minimum (m a.s.l.)	Maximum (m a.s.l.)	Mean (m a.s.l.)	p-value (Two-tailed)
Low water levels of the lake (February-July in each year)	1960- April 1996 (no regulation and only natural conditions governed variability of lake water level)	1785.10	1786.26	1785.63 (±0.25)	–
	May 1996-Dec. 2000 (onset of Tis Abay I hydropower (HP))	1785.72	1786.53	1786.12 (±0.23)	< 0.0001
	Jan. 2001- April 2010 (additional Tis Abay II HP and Koga Irrigation projects were operational)	1784.40	1786.69	1785.40 (±0.45)	< 0.0001
	May 2010- Dec. 2013 (onset of Tana Beles HP, while Tis Abay I and II HP were mothballed)	1784.79	1786.67	1785.99 (±0.52)	< 0.0001
High water levels of the lake (August-January in each year)	1960- April 1996 (no regulation and only natural conditions govern variability of lake water level)	1785.67	1787.40	1786.48 (±0.36)	–
	May 1996-Dec. 2000 (onset of Tis Abay I HP)	1786.63	1787.73	1787.15 (±0.32)	< 0.0001
	Jan. 2001- April 2010 (additional Tis Abay II HP and Koga Irrigation projects were operational)	1785.55	1787.38	1786.39 (±0.42)	0.103
	May 2010- Dec. 2013 (onset of Tana Beles HP, while Tis Abay I and II HP were mothballed)	1786.03	1787.75	1787.18 (±0.39)	< 0.0001

Water level duration curves (Fig. 6.8), which show the fraction of time that a specified water level is equaled or exceeded, also confirm the significant impact of the regulations undertaken in different periods on the lake level. The two periods of regulation, May 1996-Dec. 2000 and May 2010- Dec. 2013, resulted in a significant increase of the lake levels from the natural lake level regimes. However, we noticed a drastic decrease by 10% of the lowest water levels for the later regulation period and for the period 2001-April 2010 (Fig. 6.8) owing to the drought in 2003 and to the transition period effects as there were large water withdrawals from the lake in the preceding months for the Tis Abay II hydropower plant (before May 2010 and the water withdrawal for the new Tana Beles hydropower plant followed from May 2010 onwards).

The high water levels were apparently regulated similarly to the natural condition, while significant disparity was observed for the low water levels, during the Jan. 2001- April 2010 period of regulation. The other important aspect to notice from Fig. 6.8 is that the range of lake level variability has increased due to regulation. Under natural conditions, inter-annual variability (i.e. between years fluctuations) of the lake level occurred within a range of 1-2 m, while it is 1.3-2.6 m in the regulation period.

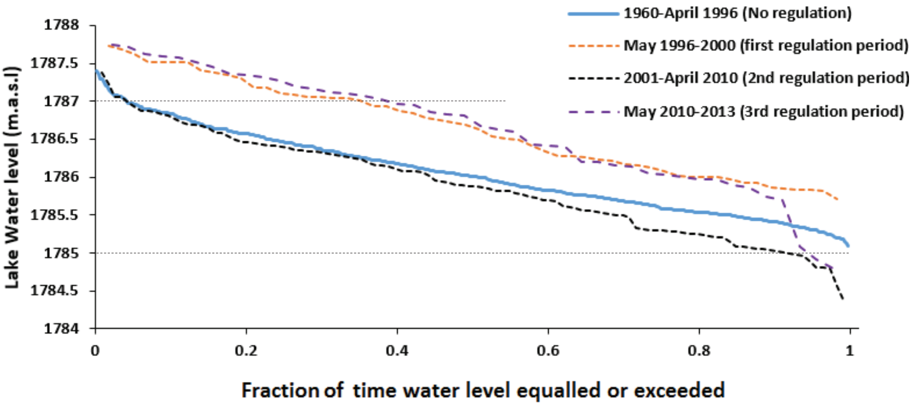

Figure 6.8: Lake Tana water-level-duration curves (plots) for the different regulation periods

6.3.3 Simulated inflows and lake levels when all planned projects are realized

Fig. 6.9 illustrates the anticipated water levels of Lake Tana for the different hydrological conditions and when all the possible water resources development projects are fully realized in the basin. In all cases, the lake level variability is strongly linked to the rainfall conditions in the basin such that the lake level starts to rise in June from its minimum (for example of 1785.64 m a.s.l in 2013), reaching a peak level in September corresponding to the effect of the June-September rainy season in north west Ethiopia. However, lake levels drop appreciably when all planned projects are accounted for in the basin. We note that the drop in lake level can be as low as 1784.96 m a.s.l considering an average hydrological condition (scenario 2, Fig. 6.9) and further reduce to 1784.69 m a.s.l for the low flow scenario (scenario 3).

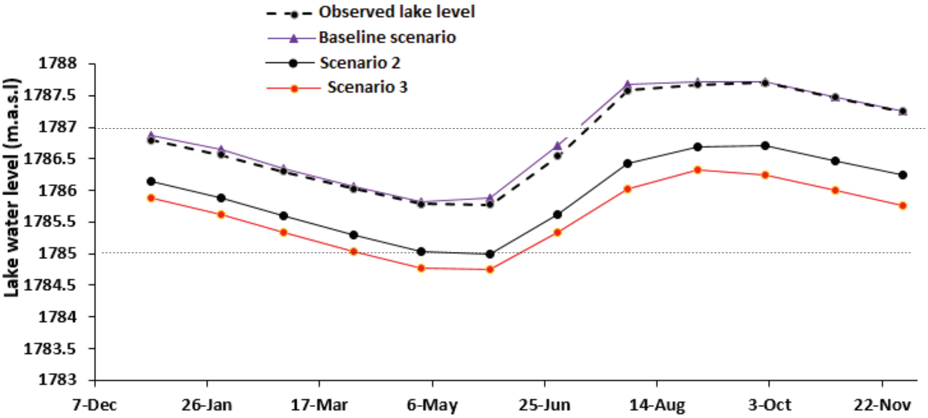

Figure 6.9: Current (year 2013) and predicted lake levels of Tana for the different scenarios

The river discharges into Lake Tana are estimated to decrease by ca. 27% from the average hydrological condition inflows when all planned water resources development projects will be implemented in the basin (Table 6.7). There will be no spill or excess flow above the gate sill levels (the weir regulates water storage in Lake Tana over a 3 m range of water levels from 1784 m. a.s.l. to 1787 m. a.s.l) as the lake level remains much below 1787 m. a.s.l throughout the year. After all projects in the basin are realized, the flow discharge through the Blue Nile outlet of the Lake to the Blue Nile Falls corresponds to the flow discharge released owing to the environmental flow requirements (Table 6.7). The annual lake level variability will also drop further even from the 2013 lake level variability.

Table 6.7: Estimated inflows into Lake Tana from its tributaries and outflow from the lake into the Blue Nile falls after all planned projects are developed

Month	Tributary inflows to Lake Tana (Mm^3)				Outflow from the lake into Blue Nile Falls (Mm^3)		
	Year 2013	Average hydrological condition	Scenario 2	Scenario 3	Year 2013	Scenario 2	Scenario 3
Jan	116	101	29	7	54	68	68
Feb	95	83	29	11	25	56	56
Mar	97	84	40	22	23	42	42
Apr	87	75	52	35	21	28	28
May	129	113	12	0	43	22	22
Jun	263	229	13	0	24	21	21
Jul	1751	1523	1115	779	36	39	39
Aug	2083	1813	1552	1152	157	83	83
Sep	1140	992	898	705	1042	192	192
Oct	568	494	394	283	406	117	117
Nov	160	139	54	24	264	109	109
Dec	109	95	25	4	141	86	86
Total	**6597**	**5739**	**4211**	**3021**	**2235**	**863**	**863**

6.4 Discussion

6.4.1 The change in the natural hydrological regime of the lake and its implications

The results (section 6.3.2) show that Lake Tana level has significantly changed its natural hydrological regime with respect to both the low and high water levels, after the lake level regulation started in response to projects (mainly hydropower) that depend on the lake water. In most of the regulation periods, the impact resulted in a significant increase of the lake levels above the natural lake level. This has led to increased backwater effect and sediment deposition in the river channels draining into the Lake Tana (Abate et al, 2015). Moreover, the long term lake level fluctuations have increased significantly due to regulation.

A significant deviation of the lake regime from its natural regime, be it a decrease or an increase in the lake water levels, has its own ecological and social consequences. Several researchers (e.g. Riis and Hawes, 2002; Chow-Fraser, 2005; Hofmann et al., 2008) reported that the composition and diversity of aquatic species is strongly connected to short-term to intra-annual, and long-term water level fluctuations. A small range of lake level fluctuations are associated with narrow, poor fringe habitat having a low biodiversity and it is more likely for fringe areas of such lakes to transform easily from aquatic ecosystems to terrestrial ones (Coops et al., 2003; Hudon, 1997). Decline of lake levels result in reduction of marginal zones around the lake and could deteriorate the whole lake leading to serious ecological degradation (Sellinger et al., 2008). In line with the implementation of the planned projects (mainly irrigation projects) in the Lake Tana basin, a drop of the lake level will occur in the near future.

Lake Tana and its surrounding wetlands are known for their large biodiversity, making the area as one of the top 250 lake regions of global importance for biodiversity (Awulachew et al., 2009). The lake inhabits nearly 65 fish species (some endemic) and at least 217 bird species can be found in the area (McCartney et al., 2010). However, following the implementation of Tis Abay II hydropower project in 2001, the lake level was reduced to its lowest recorded level in 2003 (Fig. 6.8). This had noticeable consequences on the lake and its ecology including desiccation of reed beds and consequent loss of fish breeding habitat, extended crop production of the lake bed and navigation difficulty.

Following the implementation of all the large-scale irrigation schemes, there will be a change in stream flows (minimal overbank flooding) and a decline in water quality (due to increased irrigated land and the need to apply more fertilizer and chemicals). Land use changes are also anticipated (wetlands to cultivated land as a result of increasing population pressure). These effects can modify the wetlands around Lake Tana by changing the hydrological regimes and the flora and fauna that are adapted to the fragile ecological settings of wetlands, which calls for an integrated economic and human development which is socio-culturally and ecologically sustainable.

In response to the upcoming projects in the basin and following the challenges to allocate water among various sectors, it is critical to have adequate knowledge on the optimal water level fluctuations of Lake Tana to sustain biodiversity of the area.

6.4.2 Water shortage and the tradeoffs between the water use sectors in the basin

Livelihood systems in the Lake Tana basin, like other parts of the country, are mostly dependent on rain-fed agriculture and are subjected to poverty and food insecurity mainly during periods of drought. Despite its potential and national significance for development, there is currently very little irrigated agriculture in the basin. Hence, the need for an increased use of water resources in the basin is unquestionable. Agriculture, energy, environment and transport are the major competing water-using sectors that depend on the waters of the lake and its tributaries in the Lake Tana basin.

For an average hydrological condition in the basin (scenario 2), the minimum lake level obtained from the simulated lake level was 1784.96 m a.s.l (Fig. 6.9), almost equal to 1785 m a.s.l. (the minimum lake level required for boats to navigate on the lake). Hence, this scenario-based study shows that the available water resources satisfy the water demands of all the aforementioned sectors for an average hydrological condition (scenario 2) along with proper and efficient water resources management, despite the reduced lake level fluctuations and the corresponding impacts on the fringe areas of the lake. This is based on the premise that the Tis-Abay I and II hydropower projects remain suspended as long as the Tana Beles Hydropower is functional.

The historical flow data analysis indicates that at least once in ten years, there is a low flow hydrological condition in the basin (Fig.6.8 and Scenario 3). During such events, the available water resources fail to meet all the demands of the sectors. Although it is not addressed in this study, it is possible that climate change could also affect the water supply as the basin's water resources are highly vulnerable to changes in rainfall and temperature, particularly the lake.

Under scenario 3 (Fig. 6.9), we examined the water allocation conditions during shortage of supply (low flow hydrological condition) when all water resource developments are realized. In this analysis, priority was given to the irrigation and hydropower projects and keeping the required minimum discharges for the environment from the lake (Blue Nile minimum discharges). Under this consideration, the simulation results (Fig. 6.9) show that the lake levels can drop to 1784.69 m a.s.l. Navigation on the lake can cease for at least three months (mid-April to mid-June) and possible degradation of the lake ecosystem in response to the low lake levels. The other option was also investigated, where priority was given to hydropower projects and navigation keeping environmental releases from the lake unaffected (Table 6.2). In this option, only 67% of the demand for irrigation is met (Table 6.8) and results in a reduction of about 40,000 ha irrigated land in the basin. Hard decisions will have to be made for appropriate water allocation strategies during such conditions. Consequently, it will be necessary to establish water-allocation priorities and maintain an upstream–downstream cooperation in the management of the water resource in the basin. Allocation of available water across different sectors has to be integrated into the overall economic strategy of the basin based on optimization concepts in order to maximize benefits and minimize the environmental impact. Central to this goal will be the involvement of all the stakeholders in the decision process.

Table 6.8: Estimated water allocation for the different water use sectors in the Lake Tana basin during scenario 3 if priority is given to hydropower and navigation

Month	Water allocation for irrigation under Scenario 2 (Mm^3/month)	Water allocation for irrigation under Scenario 3 (Mm^3/month)	Water allocation for hydropower under both Scenario 2 and 3 (m^3/month)	Water allocation for environmental flow from the lake under both scenarios (Mm^3/month)	Water allocation for navigation during Scenario 3
Jan	289	189	259	68	Lake water level is kept above or at the minimum required for navigation i.e. 1785 m a.s.l
Feb	251	167	215	56	
Mar	244	166	244	42	
Apr	145	109	235	28	
May	35	24	225	22	
Jun	0	0	171	21	
Jul	0	0	230	39	
Aug	0	0	245	83	
Sep	10	10	204	192	
Oct	91	67	169	117	
Nov	112	69	220	109	
Dec	85	40	247	86	
Total	1262	842	2664	863	
% total demand met	100	67	100	100	100

McCartney et al. (2010) highlighted a number of observed issues connected to the currently operational projects in the basin, such as lack of transparency and participation in decision making related to the operation of the dam that regulates the outflow from the lake, difficulties in obtaining data and information to make informed assessments of the benefits and costs of the dam for its operation and little understanding of the likely impacts of the schemes. The main outcomes of this study from the decision support system developed in the basin are summarized using a flow chart (Fig. 6.10).

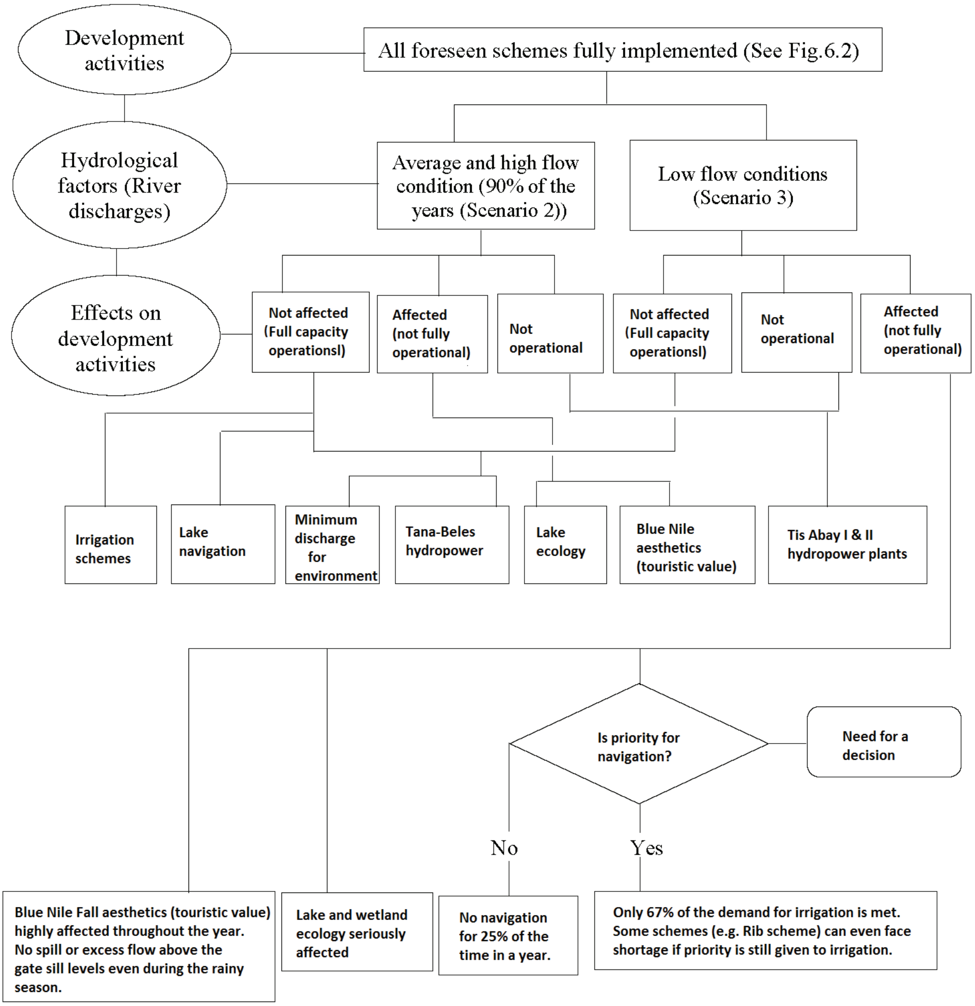

Figure 6.10: Flow chart showing implications/consequences when all planned projects will be implemented in the basin

6.5 Conclusions

Despite its potential for irrigated agriculture, the water resources of the Lake Tana basin are currently largely unexploited for irrigation purposes. However, works have already begun to realize planned water resources development projects to harness and utilize the available water resources in the basin. It remains necessary to ensure that such developments are sustainable and do not adversely affect the ecosystem and communities. In this chapter, analyses of future scenarios of water demand and supply and an assessment of trade-offs for water allocation across the different water use sectors is made as a decision support to optimally manage the natural resources and to reduce the vulnerability of water ecosystems.

Since the start of flow regulation of the lake, the lake has undergone a series of different regulation periods and each period of regulation affected significantly the lake level from the natural condition. In most of the regulation periods, the impact resulted in a significant increase of the lake levels from the natural lake level regimes. However, following the implementation of Tis Abay II hydropower project in 2001, the lake level was reduced to its lowest recorded level in 2003. The long-term lake level fluctuations have also increased significantly due to regulation.

Agriculture, energy, environment and transport are the major competing water-using sectors that depend on the waters of the lake and its tributaries in the Lake Tana basin. The available water resources can satisfy the water demands of all the aforementioned sectors for an average hydrological condition along with proper and efficient water resources management, despite the reduced lake level fluctuations and the corresponding impacts on the fringe areas of the lake. This is based on the premise that the Tis-Abay I and II hydropower projects remain suspended as long as the Tana Beles Hydropower is functional. However, during low flow conditions (expected once in ten years in the basin) supply will run short of demands and the lake water level can drop as low as 1784.69 m a.s.l if priority is given to other sectors than navigation on the lake or lakeshore ecosystems.

An upstream-downstream cooperation, transparency and participation in the decision making and establishment of adequate data acquisition systems are critically important elements in the management of the water resource in the basin. Reservoir operation rule curves need to be designed not only to match the project specific demand requirements but also to account for the optimal water level fluctuations for a good hydrological condition to obtain high species richness and sustain biodiversity of the area. This may lead, in dry years, to the need to fill the lake from reservoirs in the basin so as to maintain the minimum lake level at 1785 m a.s.l.

The results of this study are useful to indicate directions for the better planning and management of water resources in the basin as well as for the country. However, there are still various sources of uncertainty and errors in this study, such as uncertainties related to water demand assessments, hydrometeorological data quality and quantity, hydrological model, data related to catchment characteristics and reservoir evaporation estimations. The decision process needs to note such uncertainties on the results of this study.

CHAPTER 7

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7. General conclusions and outlook

In this final chapter, the major conclusions (Section 7.1) and the implications of the study (Section 7.2) are presented. Section 7.3 elaborates some topics that need further research.

The sustainable and rational development and management of water resources need a profound understanding of the different hydrological variables such as quantity and quality of available water, hydrological processes, spatial and temporal variability of runoff and water demands.

Based on the problem statements (Chapter 1), the following objectives were formulated:

- The overall objective of this study was to improve our understanding of the hydrology of the Lake Tana area in order to better plan and manage its water resources for a sustainable development.
- The specific objectives of this study were:
  i. to assess the temporal (daily and seasonal) and spatial (between catchments) variations of runoff in the Lake Tana basin;
  ii. to assess the effects of the floodplain on river discharges into the lake;
  iii. to develop conceptual hydrological models and analyze rainfall-runoff processes in the basin;
  iv. to establish water budgets of the lake and to simulate lake level changes under different scenarios; and
  v. to assess the impacts of upcoming water resources development projects in the basin on the lake for a decision support in the planning, management and water allocation strategy of the different water use sectors.

In order to meet the above objectives and research questions raised in Section 1.2.2, more than 15 hydrometric stations were established in the basin for water level measurements and sediment sampling. The water levels were converted into river discharges using appropriate rating curves. This discharge monitoring campaign has increased the size of the gauged catchment in the basin to 60%, producing river discharges of very fine time resolution (discharges at intervals of 10-30 minutes).

7.1 Major conclusions

7.1.1 Spatial and temporal variability of runoff in the Lake Tana Basin

The spatial and temporal variability of runoff in the basin was examined to meet the research objective specified in Section 1.2.1 under (i) and to answer research questions indicated in Section 1.2.2 under (i) and Questions 1 and 2. Significant variations of runoff for both spatial and temporal considerations were found.

On average, 88% of the total runoff observed from the monitoring stations in 2012 occurred in the period of June-September (the rainy season in Ethiopia). The runoff response is smaller at the beginning of the rainy season (June) than towards the end, reaching its climax in August. A closer look at the flood events in the catchments (at a time scale of one day) showed that the largest part of the runoff in the majority of the monitored catchments took place in the form of flash floods (average flood duration lasting not more than 3-5 hours). Exception to this are flood events for the Gilgel Abay River and for the other major rivers in the floodplain where most of the flood discharges lasted more than 15 hours.

The total annual runoff coefficients ranged between 0.23 and 0.81 in 2012 in the basin. The highest runoff values were observed in the Gilgel Abay catchment (0.81). On the other hand, the runoff coefficients for the Rib sub-catchment are exceptionally small. This is attributed to the high actual evapotranspiration and/or a discharge of groundwater that is not captured by the gauge measurements. Given the poor rainfall station density, an overestimation of the areal rainfall in the sub-catchment can also reduce its runoff coefficient owing to the mountainous nature of the area and high orographic rainfall variations.

Catchment variations in terms of drainage density, topography, lithology, land use, and rainfall were found to affect the summer season runoff depth and runoff coefficients in the Lake Tana basin. Discharge varied depending on drainage density (r = 0.75), lithology (r = -0.72 for percentage of Tertiary igneous rocks) and land use/land cover conditions (r = 0.61 for dominantly cultivated land with no significant other land use types).

7.1.2 Effects of the floodplain on river discharges into the lake

Lake Tana is associated with an extensive floodplain adjacent to the lake and its lowland tributaries. In Section 1.2.2, the following research question was raised: *How can we explain the hydrological processes in the floodplain? What is the impact of the floodplain on river discharges into the lake?* The answers were already obtained throughout the different chapters, mainly in chapters 3 and 5.

The studies indicated that the relevant hydrological processes in the floodplain are (1) at the beginning of the rainy season, the floodplain is recharged with groundwater, supplied by the higher elevated areas. The floodplain is also recharged by infiltration of rainfall and by the rivers that release water to the floodplains as overbank flows. (2) Proceeding to the main rainfall of July and August, these recharging components are still active and contribute to the floodplain aquifer's saturation. At this point, part of groundwater is still flowing into the lake and part of it is released into the rivers that are the main draining systems of the floodplain. (3) During the saturation periods (end of July and August), accumulation of excess water on the surface of the floodplain that spills over the river banks during floods takes place, which will later partly flow back to the rivers once the flood recedes, and partly will be lost as evapotranspiration. Until the middle to end of July, the dominant hydrological process in the floodplain is recharge of the floodplain, and runoff response from the floodplain starts after that moment.

Analyses revealed that the floodplain abstracted 809 mm of water with a corresponding increase in floodplain storage of 992 mm during the beginning of the rainy season (June to July) and released stored water starting from August until the middle of September in 2012. However, the annual water balance indicated that the runoff contribution from the Rib and Megech floodplains is negligible. But the floodplain downstream of the Gumara River showed a considerable runoff contribution to the river, also in relation to the presence of springs. The floodplain acts as storage of flood water, and consequently the magnitude of peak floods was on average 71 m^3/s (or 30%) smaller downstream than upstream in the floodplain. The peak discharges of rivers in the floodplain of Lake Tana basin are buffered by the floodplain.

7.1.3 Hydrological modeling

Hydrological models representing the underlying hydrological processes help to predict river discharges from ungauged catchments and allow for an understanding of the rainfall-runoff processes in the catchments. Hence, a simple hydrological model was developed to contribute to the understanding of the hydrology of the Lake Tana basin and to answer research questions stated in Section 1.2.2: *How are the rainfall-runoff processes of the basin explained? Can we identify the prevalent runoff mechanism and quantify the magnitude as well as the variability of the different runoff components (direct runoff, subsurface runoff and baseflow) among the different catchments of the major rivers in the basin?*

A runoff hydrograph consists of three components, namely direct surface runoff (overland flow), interflow (subsurface flow) and groundwater flow (baseflow). The hydrological model study results indicate that about 65% of the runoff appears in the form of interflow in the Gumara study catchment, and baseflow constitutes the larger proportion of runoff (44–48%) in the Gilgel Abay catchment. Direct runoff represents a smaller fraction of the runoff in both catchments (18–19% for the Gumara, and 20% for the Gilgel Abay) and most of this direct runoff is generated through infiltration excess runoff mechanism from the impermeable rocks or hard soil pans. The study reveals that the hillslopes are recharge areas (sources of interflow and deep percolation) and direct runoff as saturated excess flow prevails from the flat slope areas. Moreover, the model study suggests that identifying the catchments into different runoff production areas based on topography and including the impermeable rocky areas separately in the modeling process mimics the rainfall–runoff process in the basin well.

The hydrological model has also been applied to predict river discharges for the ungauged catchments in the basin. The test for the direct transfer of calibrated model parameters to other nearby ungauged catchments (e.g. Dirma catchment) was satisfactory for a preliminary planning and quantification of water resources. Transferability of the model has benefited from the fact that most of the input data were derived from the ungauged catchments.

7.1.4 Lake water balance

Lake Tana provides variety of services for humans and ecosystem functioning. For its sustainable use, it is necessary to address research questions related to its water balance and impacts of the floodplain on the water balance raised in Section 1.2.2 as: *What is the water budget of the lake and how is the floodplain buffering affecting the water balance of the lake? Which parts of the lake basin generate most of the runoff to the water balance of the lake? How can the different uncertainties in the water balance terms of the lake be explained and compared with previous studies?*

The detailed daily water balance analysis for Lake Tana revealed that there was an average yearly abstraction of 420 x 10^6 m^3 or 6% of river inflows to the lake by the floodplain in 2012 and 2013. Nearly 60% of the inflow to the lake is from the Gilgel Abay River. From the water balance analysis, the water budget components of the lake were found as a mean lake rainfall depth of 1330 mm, open water evaporation depth of 1789 mm, river inflow depth of 2201 mm and outflow discharge depth from the lake of 1618 mm. Simulated lake levels compare well with the observed lake levels ($R^2 = 0.95$) and the water balance can be closed with a closure error of 82 mm/year (3.5% of the total lake inflow).

There are still several sources of uncertainty and errors in the water balance. This study, unlike the previous water balance studies, is more comprehensive by providing a separate analysis of the floodplain and the catchments influenced by the floodplain. Uncertainties of the runoff estimations from ungauged catchments is also reduced by reducing the ungauged catchments from about 60% to 40%. The river inflow estimates by the previous studies are smaller than that reported by this study, and even for some of the studies the estimates were found so small in that negative inflows for some months were observed when a monthly runoff series for the combined ungauged areas was made. The most likely reason for this is because of the abstraction of water by the floodplain (via runoff transmission losses), as revealed in this study. Hence, this study demonstrated the importance of floodplains and their influence on the water balance of the lake and the need of incorporating the effects of floodplains and water abstraction for irrigation to improve predictions.

7.1.5 Planned water resource developments and their implications on Lake Tana

The Lake Tana area is identified as one of the growth corridors in the country following its significant water, land, livestock, forest and fishery resources; a rich cultural heritage and natural assets; relatively developed urban centers and dense settlements; good roads and air connectivity. Analyses of future scenarios of water demand and supply and an assessment of trade-offs for water allocation across the different water use sectors have been made as a decision support for a better management of water resources in the basin. The inflows to Lake Tana are estimated to reduce by about 27% when all planned water resources development projects are implemented in the basin. These projects result in the generation of 560 MW hydroelectric power and about a billion m^3 per annum supply of water to the large-scale irrigation schemes. During low flow conditions, supply will run short of demands and the lake water level can drop by 0.3 m from the natural outlet level of 1785 m a.s.l. The lake experienced four periods of different flow regulations since monitoring of the lake water level started. Generally, lake water levels and long term lake level fluctuations have been affected significantly due to regulation with subsequent impacts on the lake ecology. Following the implementation of Tis Abay II hydropower project in 2001, the lake level was reduced to its lowest recorded level in 2003. It was characterized by its noticeable consequences on the lake and its ecology including desiccation of reed beds and consequent loss of fish breeding habitat, extended crop production of the lake bed and navigation difficulty.

An upstream-downstream cooperation, transparency and participation in the decision making and establishment of adequate data acquisition system are critically important elements in the management of water resources in the basin.

7.1.6 Uncertainties and implications on the results of the study

We tried to discuss the various uncertainties and limitations in the respective chapters in the dissertation. It is also worth mentioning here. The runoff coefficients for some catchments, particularly for the Gilgel Abay catchment, are very high. Data are scarce in the study region and may be confronted with uncertainties in their measurement. Because of a shortage of measurement stations, areal rainfall interpolation methods could not be validated. The floodplain studies were based on upper versus lower discharge observations and further detailed water balance studies of the floodplain would require validated estimation of actual evapotranspiration. Hence, the study is a preliminary work to be used as a background for further research. We understand the limitations of our study and the results have to be further verified as additional data become available through a detailed mass balance analysis. Possible efforts have been made to develop a simple conceptual hydrological modelling in chapter 4 and it has been applied to estimate discharges from ungauged catchments for the different purposes in the dissertation. However, like any other models, we cannot also rule out the uncertainties in this model. There are many sources of errors that could influence the absolute model results. For example, soil-based information is derived from studies previously performed in the region and literature recommendations. Nevertheless, the outcome of the model is confirmed by other models and by field expertise. As such, the results obtained can be used as indicative for the hydrological processes occurring in the Lake Tana region, and therefore enhances our understanding of the system.

7.2 Significance of the study and implications

The outcomes of the study contribute to proper planning and management of land and water resources of the Lake Tana basin and are believed to be applied by the different stakeholders involved in the basin. Moreover, the study may serve as a guiding reference to the scientific community and practitioners in the area of water resources systems as most of the research results are published in peer reviewed journals.

i. Runoff and sediment data

Different water resources development interventions and research activities in the Lake Tana basin are usually constrained by limited data availability and reliability on runoff and sediment. In this study, we generated additional data sets on runoff and sediment with better quality and coverage in the basin and can, therefore, be used by the stakeholders and the scientific community, who are involved in planning, design, and research activities in the basin and similar catchments in northern Ethiopian highlands.

ii. Runoff estimations for ungauged catchments

We developed a simple robust hydrological model which is based on catchment soil moisture status and topography and minimal model parameters. It can be used for preliminary assessments to estimate runoff volumes for the ungauged catchments by the engineers and planners during the design of dams for various purposes.

iii. Lake, wetland and floodplain management

Lake Tana and the surrounding wetlands have immense ecological value and provide livelihoods for millions of people. The results of this study, mainly on the water budgets of the lake and the hydrological processes of the floodplain, will have positive implications for those involved in the conservation and management of the ecosystem. The floodplain hydrology study conducted in this study is the first of its kind for the area and is expected to trigger similar studies for a better understanding of the river-floodplain-lake interactions.

7.3 Future perspectives

During the course of this study, we encountered various problems and uncertainties that could not be solved and need to be addressed in future research. Here, we list the most important ones.

i. Continued monitoring of the current runoff stations, establishing additional stations and detailed characterization of their catchments are very important for a better understanding of the hydrology of Lake Tana basin. The new monitoring stations are needed for monitoring Garno, Gumero for the northern part of the basin and other selected catchments for the southern part of the basin. Reliable spatial data and fine-tuning of soil and land use maps is important for better modelling of runoff.

ii. Water level measurements from the different monitoring stations were converted into discharges using rating curves. The rating curves (flow depth-discharge relationships) were developed using average velocities, derived from the float velocity measurements. The average velocities were obtained from literature recommendations and calibration results of the current meter and float method velocity measurements conducted in the field for low flow periods. However, further research is needed to establish improved relationships between both methods of flow velocity measurements including velocity measurements for the high flow (flood) conditions.

iii. The hydrological model developed was applied for different sizes of catchments in the Lake Tana basin. We have come across the fact that the model performance mostly decreased for smaller catchments and hence the modelling scale affects its performance. Model uncertainty studies by Loosvelt (2013) show that the larger the modelling scale, the less uncertainty is involved. The reasoning is that errors at the point scale compensate each other when averaged over the catchment such that the resulting error at the catchment scale is significantly lower. This effect is quite similar to the increasing complexity of natural processes at the finer scale, which is in contrast with the relative simplicity of large scale processes. Therefore, further research involving tests and improvements of the model for the smaller catchments are suggested.

iv. The Lake Tana floodplain is less researched area and availability of data is still a bottleneck. We used the simple computation-based estimate by subtracting upstream from downstream discharge measurements to fairly understand the hydrology of the floodplain. Wetlands and floodplains are important ecosystems providing the biosphere with valuable services and functions. Hence, further research and data acquisition is important to get a detailed understanding of its hydrological processes and sedimentation in the floodplain.

v. Lake Tana has a very large surface area unlike its shallow depth (average depth ca. 9 m) and consequently a 1 cm variation on its water level brings about a change in the storage volume of the lake equivalent to 30×10^6 m^3. This shows that the rainfall and evaporation water balance terms of the lake are very sensitive and uncertainties related to the determination of their quantities affects the water budgets of the lake strongly. Hence, for further refined quantification of the water budgets of the lake, more research and data acquisition on the lake rainfall and evaporation is highly recommended.

vi. In line with the implementation of the different planned water resources development projects in the Lake Tana basin, the demand for water will increase in the coming years. This calls for a detailed water allocation model based on multi-objective optimization and for an integrated water resources management to increase water use efficiency and sustainability in the basin.

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2. Education

B.Sc. Programme (B.Sc. Degree in irrigation engineering with distinction)

1990-1995	Arba Minch Water Technology Institute (Now Arba Minch University), Ethiopia *Thesis: Design of a small scale irrigation project in Endadeko, Eritrea* Supervisor: dr. Pandey B. B. Lal

M.Sc. Programme (M.Sc. Degree in water resources management)

2003-2005	University Luneburg, Niedersachsen, Germany *Thesis: Water Budget analysis and water management in irrigation schemes: A case study on the Belbelit Small-Scale Irrigation Project in Ethiopia* Supervisor: Prof. dr. Brigitte Urban

3. Work Experience

1996-2003	Co-SAERAR (Commission for Sustainable Agriculture and Environmental Rehabilitation in Amhara Region, Ethiopia **Position**: Senior design engineer **Responsibility**: Study, design and supervision of water resources projects
2003-2005	University Luneburg, Niedersachsen, Germany **Position:** MSc Student
2006-2007	WWDSE (Water Works Design and Supervision enterprise), Addis Ababa, Ethiopia **Position:** Senior office engineer **Responsibility:** Design engineer and Project coordinator
2008-2011	Bahir Dar University, Ethiopia **Position:** Lecturer and researcher
2011-2015	Bahir Dar University (Ethiopia) and Ghent University (Belgium) **Position:** PhD Student

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4. Publications

Dessie, M., Verhoest, N.E.C., Pauwels, V.R.N., Adgo, E., Deckers, J., Poesen, J., Nyssen, J., 2015. Water balance of a lake with floodplain buffering: Lake Tana, Blue Nile Basin, Ethiopia*. Journal of Hydrology 522: 174-186. doi:10.1016/j.jhydrol.2014.12.049*.

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